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TABLE OF CONTENTS.

No. 1.

PAGE

PERMIAN PLANTS—TÆNIOPTERIS OF THE PERMIAN OF KANSAS, *E. H. Sellards* 1
ON THE GROUP OF 216 COLLINEATIONS IN THE PLANE, *H. B. Newson*..... 13

No. 2.

ON THE GROUP AND SUBGROUPS OF REAL COLLINEATIONS LEAVING A TETRAHEDRON INVARIANT. (A NEW THEORY OF COLLINEATIONS IN SPACE, I.) *H. B. Newson*..... 33
THE DIMORPHISM OF CAMBARUS, I, *J. Arthur Harris*..... 49
SPERMATOGENESIS OF THE MYRIAPODS, I, *M. W. Blackman*..... 61

No. 3.

ACTION OF LIQUID AMMONIA ON ACID CHLORIDS AND ESTERS, *Edward Bartow and D. F. McFarland* 79
A NEW THEORY OF COLLINEATIONS IN SPACE, II, *H. B. Newson*..... 87
A NEW THEORY OF COLLINEATIONS IN SPACE, III, *H. B. Newson*..... 99
COCCIDÆ OF KANSAS, IV, *S. J. Hunter*..... 107

No. 4.*

BIBLIOGRAPHY OF SCIENTIFIC PUBLICATIONS BY MEMBERS OF THE UNIVERSITY OF KANSAS, FIRST SUPPLEMENT..... 149
LIST OF PUBLICATIONS RECEIVED IN EXCHANGE FOR THE KANSAS UNIVERSITY QUARTERLY..... 159
CONTENTS OF KANSAS UNIVERSITY QUARTERLY, VOLS. I-X..... 169
INDEX TO AUTHORS TO KANSAS UNIVERSITY QUARTERLY, VOLS. I-X..... 177
SUBJECT INDEX TO KANSAS UNIVERSITY QUARTERLY, VOLS. I-X 187

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CONTENTS:

I.—PERMIAN PLANTS—TAENIOPTERIS OF THE PERMIAN OF KANSAS, ... *E. H. Sellards.*

II.—ON THE GROUP OF 216 COLLINEATIONS IN THE PLANE, *H. B. Newson.*

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VOL. X. JANUARY, 1901. No. 1.

Permian Plants—Taeniopteris of the Permian of Kansas.[1]

Contribution from the Paleontological Laboratory No. 58.

BY E. H. SELLARDS.

With Plates—I, II, III and IV.

The fern genus, *Taeniopteris* Brongniart, is well represented in number of individuals, in the Kansas Permian Flora, on which the author is working, and presents aside from the presence of at least two species and one variety, some interesting features. The rachises of several of the ferns bear elliptical scars, which, as I will attempt to show, are very similar to, if not identical with the scars on *Macrotaeniopteris magnifolia* (Rogers) Schimper from the Richmond coal fields of Virginia, Jurassic, regarded by some authors as scars marking the position of the sori of the genus. The second character of especial interest is the presence between the veins of small, oval resistent bodies, sporangia (?), fungi, or possibly interneural glands. The plants described come from three miles south and one-half miles east of Banner City, Dickinson county, Kansas; a few also from the same horizon three miles south of Carlton, Kansas. They were collected in part by Mr. Charles Sterling of the University, and in part by the author. The formation is probably the Marion of Prosser. The plant horizon is within a few feet vertically of the plant-bearing Cretaceous strata. The photographs and drawings were made by the author, except figure 7, plate 1, made by Mr. Sidney Prentice.

1 Published by permission of the paleontologist of the University Geological Survey of Kansas.

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The author is very much indebted to Dr. David White, curator of the Palaeozoic plant collections of the United States National Museum, not only for the kindest advice and suggestions, but for the favors of access to the collections in his charge, and assistance in finding the plants of most interest in their relation to the Kansas forms.

Systematic Description.

TAENIOPTERIS.

Brongniart. Prodrome, p. 61, 1828

Taeniopteris coriacea Goep. Plate I, Figs. 6, 8–12; Plate II; Plate III, Figs. 1, 2; Plate IV, Figs. 1, 3.

Taeniopteris coriacea Goeppert. Flora der Permischen Formation, p. 130, Plate VIII, Fig. 4; Plate IX, Fig, 2, 1865-1866.

Fronds simple (?), linear or very narrowly elliptical, coriaceous in texture, broadest in the middle, tapering to a symmetrical lanceolate apex, and a petiolate base, 8 to 20 cm. long, average width at the middle, 10 to 20 mm.; rachis strong at the base, rough with rather strong, longitudinal striae, about 3 mm. wide, reduced gradually in passing to the apex where it becomes a mere line; fronds slightly rolled at the borders; lateral veins numerous, strong, straight and parallel, cross the lamina obliquely, with a slight but distinct upward curve at the border, 28 to 32 per centimeter; veins near the base of the frond leave the rachis with a short curve, often forked once near their base; those at the middle of the frond only slightly curved at their union with the rachis, seldom forked; those near the apex not at all curved at their base, always simple, straight, or even arched upwards slightly in crossing the lamina; oval bodies, sporangia (?) on several of the fronds, situated between the veins, half immersed in the epidermis of the frond, ½ to ¾ mm. apart, six or seven between each two veins; elliptical elevations, or corresponding depressions occur on or near the rachis of several specimens.

The species is a common one, and is represented by many good specimens. By reason of the thick resistant texture, the frond is usually well preserved, and forms a natural line of cleavage in the matrix, which often breaks so as to expose its entire length. The individual specimens vary a good deal in size, but can usually be readily recognized by their straight, oblique, strong nerves, resistant texture, and lanceolate apex.

The agreement with Goeppert's types is not entirely complete, but essentially so. Goeppert's figures do not show a rolled border,

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nor does he mention such a character in his description; but this character is not always evident, and possibly not always present.

I have considered the frond as probably simple, as there are no indications of a pinnate character, and it has the same shape as other *Taenioptorids* with supposedly simple fronds. The peculiarities of venation noted in the above diagnosis—veins near the base of the frond more curved at their union with the rachis, often forked, while those at the apex are only slightly curved, seldom forked,—are seen also in the figures of the European specimens. The texture and shape of the fronds also agree. The fact that the oval bodies between the veins have not been previously observed may be due to the rarity of the species and the few specimens heretofore obtained. The scars on or near the rachis, whether the result of fungi or of insect stings may have been absent on the European specimens.

The slightly thickened and rolled border of this species might be taken to indicate the presence of a border vein—a supposition to which the upward curve of the veins at the border adds strength. But if such a character belongs to the species, it is not sufficiently preserved on any of the specimens at hand to be recognizable. Such a character, if it exists, would bring the species into comparison with the Mesozoic genus *Oleandridium*, some species of which it otherwise closely resembles.

The species seems to have been found as yet in only two other localities, both Permian, Ottendorf in Bohemia, and Lissitz in Moravia, both recorded by Goeppert, l. c. The specimens known of the species heretofore have all been somewhat fragmentary.

Taeniopteris coriacea var. **linearis** n. var. Plate III. Figs. 3, 4.

Fronds smaller, more narrowly linear, apex very acute, average width 7 to 20 mm , average length about 14 cm., thinner in texture, venation apparently thinner, and perhaps closer.

The difference between the extreme forms of this variety and the specimens typical of the species is very great, and if there were no intermediate forms would undoubtedly be considered of specific value. But between the extremely narrow fronds such as figured plate III, fig. 4, and those typical of the species, plate II, figs. 1 and 2, there are such continuous gradations that I am entirely unable to draw any separating line. The venation of the smaller fronds seem thinner, but becomes proportionally stronger with the size of the frond. The apex, however, is decidedly more acute. The species and variety occur at the same locality.

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Taeniopteris newberriana F. and I. C. W, Plate I, Figs. 1-5, 13, 7 (?), Plate IV, Figs. 2, 4

Taeniopteris newberriana Fontaine and I. C. White, Permian, or Upper Carboniferous Flora of West Virginia and Southwest Pennsylvania, p. 91, plate 34, figures 1–8, 1880.

Numerous specimens in the collection are so close to *Taeniopteris newberriana* that their reference to that species, at least for the present, seems advisable. There are numerous individuals, but all more or less fragmentary. Owing to the thin texture of the frond the line of cleverage in the matrix is not sufficiently marked to expose it completely as in the last species. In this character of a very thin frond our specimens differ very markedly from the types of the species, which are described by the authors as rather thick and coriaceous. The fact that the matrix is different in the two cases, ours being preserved in limestone, while theirs were in shale, may account in part for this, and possibly for other seeming differences. The nerves are figured by the authors as leaving the rachis at right angles, but in the description they say that the lateral nerves leave "the midrib at a right angle, or with a very slight arch immediately at the insertion." In our specimens the veins near the apex of the frond leave the midrib at right angle, those near the middle with a slight arch immediately at the insertion, and those near the base with a more decided arch at the insertion. In the figures of the types the veins are represented as coming out at right angles from the rachis throughout the entire length of the frond, the base as well as the apex. No specimens have been found in the Kansas formation with the peculiar segmentation characterizing many of the Virginia specimens. These two characters—difference in the origin of the veins, and absence of the segmented frond, may prove to be specific differences separating our species from Fontaine and White's. The present reference is intended as suggestive rather than final. In other respects Fontaine and White's description of the venation, "lateral nerves very fine, closely placed and immersed in the parenchyma of the frond," entirely agrees with our species, as does also their description of the size and shape of the frond, "frond, simple, elongate, narrowly eliptical, tapering slowly to the apex and base." The largest frond of our specimens are 17 to 23 mm. wide, probably not less than 20 cm. long; the Virginia specimens are 2¾ cm. wide, and have an estimated length of 20 cm.

Fontaine and White compare the species to *T. coriacea*. It differs from specimens of that species from the same locality, in a larger and much thinner frond, finer and more numerous veins,

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more nearly at right angles to the rachis. The two species are usually easily separated on these characters, but between the larger fronds of *T. coriacea* and the smaller of *T. newberriana* as represented in the Kansas Permian, the dividing line is sometimes by no means clear.

The species may be compared in venation to *T. jejunata* Grand' Eury, but this latter species is described as having a pinnate frond, of which the ultimate pinnae have a somewhat cordate base. *T. newberriana* has a simple frond gradually reduced to a petiolate base, as shown both by the Virginia and Kansas specimens. Professor Potonié, Die Flora des Rothliegenden von Thuringen, p. 145, includes in the synonomy of *T. jejunata*, "*T. newberriana* Font. and White ex parte" and cites plate XXXIV, figures 9, 9a, of the Permian Flora, but the figures referred to are not of *T. newberriana*, but of *T. lescuriana* F. and I. C. W.

The horizon from which the types of *T. newberriana* were described have been variously regarded as Permian and Permo-Carboniferous. Professors Fontaine and White in their treatment of the flora argue strongly for its Permian age.

Taeniopteris sp. Plate I, Fig. 14.

I figure here the apical part of a frond which is, probably, different from either of the other species. The venation has much the same character as that of *T. coriacea*, but the frond is evidently much larger. On the other hand the veins are very much more oblique than those of *T. newberriana*. The veins are thin and close, and the dots between the veins small and numerous.

Interneural Bodies on the Fronds of Taeniopteris.

The interneural bodies referred to in the introduction occur on some specimens of each species and variety of *Taeniopteris* in the collection. They are small, oval, resistant bodies, situated between the veins, half immersed in the epidermis of the frond, nearly globular in shape, some smooth on top, but more often showing a slit across the top or side very suggestive of the slit for the discharge of spores in many eusporangiate ferns. The slit, apparently, has no regular position on the bodies; it is sometimes across the top, sometimes on the side, sometimes parallel to the direction of the veins, or again transverse to the veins. The bodies, when removed from the epidermis leave a cup-shaped cavity. In many of the cavities there is a cast of the slit, indicating that many of the bodies had the break turned down, and doubtless many of those appearing smooth on top are slit below.

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Some of the sporangia(?), however, are certainly not slit in the manner described. One specimen of *T. newberriana* having many of the bodies preserved, has none showing the slit, and when removed and mounted they are seen to be round and entire. If we accept the hypothesis that the bodies in question are sporangia, the absence of the cleft in this specimen would naturally find its explanation in the supposition that the sporangia are not yet mature.

The size and number of the sporangia seem to be characters of specific value. On the group of specimens which I have referred to, *T. coriacea*, they are proportionally large, readily visible to the eye, more distant and fewer than in the other species. The bodies between the veins of *T. newberriana* (*?*) are smaller—although the frond is larger—closer together, and scarcely visible without the aid of a lens.

When the matrix holding the specimen is opened some of the bodies always adhere to one side and some to the other, so that either side of the specimen shows some in place and casts of others. Under a lens the bodies show distinctly. Examined under a high power with reflected light the details seen with the lens come out more definitely, the bodies appearing bright yellow in contrast with the dark substance of the frond Figures 4 and 5, plate I, are sporangia(?) taken from a specimen of *T. newberriana* (*?*) showing slits, one across the top, the other across the side. Figures 10 and 11 show two bodies taken from *T. coriacea*, and figure 12 a cast. All enlarged thirty diameters.

The bodies may be readily removed from the frond and imbedded and sectioned by grinding. On touching the epidermis with moulding wax many of them adhere and may be transferred to the desired media for sectioning. The author used for this purpose, hardened balsam and sealing wax. Of the numerous sections made none showed conclusive evidence of cellular structure—the one remaining point necessary to prove that the bodies are sporangia. Irregular markings resembling cell walls are often seen, but nothing definite. Thin sections under a high power appear minutely granular with redish-yellow granules. Chemical test shows the presence of iron, and other appearances suggest iron oxide as their probable composition.

Analogous appearances in other genera of plants—Nilssonia.

Some species of *Nilssonia* Brong., a Mesozoic genus referred to the cycads by some authors, to the ferns by others, have dots between the veins very suggestive of those of *Taeniopteris*. The dots

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on *Nilssonia polymorpha* Schenk are described as small, situated at approximately regular distances apart, between the veins. The dots of this species have been variously regarded by different authors. Schenk regarded them as the remains of sori and accordingly referred the genus to the ferns.[1] Saporta considered them more like fungi and referred the genus again to the cycads.[2] Count Solms Laubach, Fossil Botany, p. 140 (Balfours translation), in summing up the evidence considers Schenk's view more probable than Saporta's, and therefore treats of the genus among the ferns. Later authors have generally referred the genus to the cycads. Another interesting point of analogy between those specimens of *Nilssonia polymorpha* having unsegmented pinnae and the *Taeniopterids* under consideration is the striking similarity in the shape and venation of the apical part of the frond. In both the midvein is reduced to a mere line, but continues to the apex, the lateral veins are arched upwards, with numerous dots between them.

Neuropteris.

A specimen of *Neuropteris* in the Lacoe collection of the United States National Museum, which Dr. White had the kindness to show me, has dots between the veins very suggestive of the oval bodies between the veins of our specimens of *Taeniopteris*. Dr. White is inclined to regard these dots as glands. The species is described in an unpublished manuscript of Lesquereux, which Dr. White is now editing.

Alethopteris.

Andrews described in Vol. II, pal. Geol. Surv. of Ohio, p. 421, pl. 50, figs. 3-3b, a species from near the base of the coal measures of Ohio, under the name *Alethopteris maxima* And., which has numerous small dots between the veins. Andrews regarded these as probably dots of iron oxide. Lesquereux, Coal Flora, p. 187, refers to them as "remants or the base of scales similar to those often seen upon leaflets of species of *Acrostichum*."

Megalopteris

Dots occur between the veins of *M. Harttii* And. and *M. dentata* in the museum collection, from Rushville, Ohio, very like those on *Taeniopteris*.

1 Die fossile Flora der Grenzschichten des Keupers und Lias Frankens, 1868.
2 Paleontologie francaise, ser. 2, vegetaux, vol. 2, 1875.

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Other species of Taeniopteris.

Newberry figures the apex of a frond[1] with the following explanation of the figure: "*Taeniopterts* sp. (?) in fruit; summit of frond, Los Broncos, Sonora." The formation is considered Triassic. The specimen is not mentioned in the text. The figure is indistinct, but the dots seem to be small, close, and placed much as in our specimens, and are very probably the same.

Dots of the character of most of those mentioned above, whether glandular or fungal, or the bases of scales, if sought for will probably be found on many other species and various genera. Recently I have noticed very similar dots between the veins of an *Alethopteris* from Lansing, Kansas, probably *A. serlii* (Brong. Goep.

If the dots between the veins of all these various genera are the same as those on *Taeniopteris* the possibility of their being fructification is practically excluded. It is scarcely possible for genera differing so widely in form and geological position to have fructification so very similar. Two characters, however, are to be noted on *Taeniopteris* not present on any of the others: the dots are in the form of hard resistant bodies, which can be removed and sectioned, which seems not to be the case in any of the other genera; secondly, the slit in the bodies remains unexplained on any other theory than that these are sporangia and the slit the line of cleavage for the discharge of spores; to which might be added a seeming difference in the size and arrangement of the bodies on the different species. It might be argued against such an hypothesis that no genus of ferns is known in which the sporangia are placed between, and having no direct connection with the veins. In many genera they are placed between the forks, or at the ends of the veins, but always, so far as I have been able to learn, in direct connection with this source of nourishment. Such an arrangement, however, might not be impossible on a primitive fern. The solitary and distantly separated sporangia(?) are not peculiar to this genus. Several fossil genera are known in which the sporangia are often or regularly solitary; in the living genus *Angiopteris* the sporangia are independent of each other.

With the incomplete evidence at hand, especially in the absence of structual characters, no positive conclusion is possible, and the question is best left open for the present. The appearance is certainly very suggestive of sporangia, and in this journal, January,

1 Exploring expedition from Santa Fe to the Junction of the Grand and Green rivers, 1859, Macomb. Geological report by Newberry, pl. 8, fig. 5.

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1900, the author referred to them as apparently representing a new type of fructification. Unfortunately the positive proof is still lacking.

Scars on or near the Rachis of Taeniopteris.

Several specimens of this genus bear on or near the rachis, elongate-elliptical scars, resembling very closely those of *Macrotaeniopteris magnifolia* (Rogers) Schimper as described and figured by Professor Fontaine in his Monograph on the Older Mesozoic Flora of Virginia, p. 18, pl. 4, figs. 1 and 1a. Two scars are seen in succession on the rachis of *T. newberriana*, pl. 1, figs. 1 and 1a. Professor Fontaine's description is taken from the depression, while in this specimen the scars project. The counter impression in wax seems to agree in every particular with his description of "elliptical depressions surrounded by a raised line, which, sweeping sharply around the ends of the depressions, continues double until a divergence takes place to embrace the next depression." Near the apex of the same specimen a third scar occurs on the middle of the rachis. Another fragment of this species, figure 2, plate IV, has two scars of the ordinary size on the midrib and a third smaller one between these two and at the side on the lamina, about one-half mm. from the midrib. The scars on *T. coriacea* are very distinctly marked. Figure 1, plate III, shows a string of them on the rachis very suggestive of Fontaine's figure. Two other specimens have a plainly marked row of scars on the rachis. The scars have no regularity of size, distance apart, or position on the rachis. In this respect they resemble Rogers' original description for those of *Macrotaeniopteris magnifolia* in which he says that the scars are placed at unequal intervals, and at rather varying distances from the midrib, and not unfrequently on the midrib itself.

A comparison of the scars born on the rachises of the two species on which they occur has failed to bring out any constant differences between them in arrangement, structure or position. They are of various sizes, from very small, one-half mm. or less, to five mm. long, about one mm. wide. The shape is seemingly constant, elliptical with the longest axis parallel to the rachis. The depressed space around the scar, "raised line" of Prof. Fontaine's description of the counter depression, is always present, sometimes comparatively broad and well marked.

Professors Rogers and Fontaine regarded the scars of *Macrotaeniopteris magnifolia* as probably the bases of sori. But their

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presence on another genus, *Taeniopteris*, with additional evidence of their irregularity of arrangement, size, distance apart, and their position on the rachis—an unusual place for fern fructification—all argue strongly against such a conclusion. But there is more satisfactory evidence at hand that the scars can not have anything to do with fructification. A specimen of *Glenopteris splendens* Sellards, from the same locality, has an identical scar on the rachis, as noted in the description of that species, Kans. Univ. Quart., Vol. IX, No. 3, p. 184. A second scar occurs on the rachis of another specimen of the same genus, the species scarcely determinable, but probably the same. *Glenopteris* is a very different genus from *Taeniopteris* and can hardly be thought of as having the same fructification.

The presence of the scar on three genera and several species indicates that they are not the result of any accidental injury to the plant. It is difficult to make out with any degree of certainty what they are. They resemble some fungi rather closely. The possibility that they may be the result of pathological growth due to the sting of an insect naturally suggests itself and, indeed, seems very possible.

Figure 2, plate II, shows another set of markings, this time entirely on the lamina. They are elongate, or ovate-elongate, with the long axis parallel to the nerves, of varying size from very small to 5 or 6 mm., close or distant, project sensibly from the frond, usually with the carbonaceous layer rubbed off of the top. Some of the smaller ones are uninjured, and seem to show an elevated border with a depressed center. These scars are very suggestive of the work of the fungi.

The scars have an added interest because of their resemblance to scars on the type specimens of *Taeniopteris newberriana* from West Virginia, which Professors Fontaine and I. C. White regard as the basis of the sori. In the West Virginia specimens the scars are placed in a single row along each side of the midrib, and the frond is divided into segments by deep obtuse sinuses. Nothing of the segmented character has been observed on our specimens, and the large scars are more commonly on the midrib. These authors, however, compare the scars to those on *Macrotaeniopteris magnifolia* to which ours are very closely related. They say, Permian Flora, p. 93, "*Macrotaeniopteria rogersi* Schimper of the Richmond coal field, contains, on specimens in our possession, elliptical depressions strikingly like the depressions seen on this plant, and shown on plate XXXIV, figure 3. In the specimen from the Richmond coal the depressions are larger, and are

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placed in one row *on* the midrib. Professor Wm. B. Rogers, however, in his description of the plant, says that they often occur in two rows, one on each side of the midrib." It cannot be affirmed that the scars on our specimens are the same as those on Fontaine and White's specimens, but it would seem from their relations that they are at least of the same nature, and probably have no connection with fructification.

Dr. David White has had the very great kindness to look over the manuscript and illustrations of this genus, except figure 1a, plate I, which has been added. Dr. White gives it as his opinion that the rachial pits are fungi, and suggests a comparison with the genus *Rosellinites* Pot.

The comparison to insect stings was sugested to me originally by the close resemblance of the scars to the stings on the common *Amorpha fructicosa* (false indigo), said to be made by some of the orthopteroid insects, a supposition which the more recently discovered presence, among the plants, of two well preserved orthopterous insects may be taken to strengthen. The scars on this shrub are certainly similar in arrangement and shape to those on the fern rachises, although somewhat larger. The resemblance may of course be entirely superficial.

The suggested comparison with fungi is good, although I am inclined to think the comparison closer with the genus *Hysterites* than with *Rosellinites*. Quite recently I have found on a fragment of *Cordaites* from University Hill, Lawrence shales, Lawrence, a fungus related by its form, position, and the host on which it is borne, to some species of *Hysterites*, as *H. cordaites*, and at the same time so similar to the objects in hand as to suggest a close relation. A close examination of the rachial pits reveals the presence on two of them of elongate depressions at the center suggesting the cleft in the living genus *Hysterium*—to which *Hysterites* is compared—or the related *Hysteriographium*. This character is represented in the detailed figure 1a, plate I. If this figure had been made at the time Dr. White saw the plate, I am inclined to think he would have suggested *Hysterites* as well as *Rosellinites*, or possibly instead of that genus. The type species of *Rosellinites*, *R. beyschlagii* Pot., as described and figured by the author, Flora des Roth., p. 27, plate I, figure 8, is irregular in shape, varying from circular to elliptical or egg-shaped, running together in irregularly formed masses; the scars on the fern rachises are symmetrically elliptical, and do not show the various irregular enlargements seen on *Rosellinites beyschlagii*.

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These scars merit a more careful and extensive comparison with living and fossil forms than I have been able to give them. Among a few living fungi with which I have had the opportunity of making comparison, *Hystertiographium vulvatum*, kindly loaned me by Professor Barber, may be mentioned as having conceptacles shaped like the scars in question, with a central cleft that might be considered homologous with the depressed center of the scars. I have not noticed anything in the living species that seems to represent the depressed canal, "raised line," in Professor Fontaine's description.

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On the Group of 216 Collineations in the Plane.

BY H. B. NEWSON.

§1. Introduction.

The group of 216 collineations in the plane was discovered by C. Jordan and treated by him in *Crelle, Band* 84, pp. 89-215; and discussed again by him in *Atti della Reale Accademia di Napoli, Tome* 8 (1879). This group has been further studied by Maschke in *Math. Annalen, Band* 33, pp. 324-330. This paper by Maschke is the standard reference on the subject.

The object of the present paper is to study the geometric properties of the group and its sub-groups with respect to a pencil of cubic curves through nine points of inflection; to determine the types of collineations entering into the group; to determine the order of each transformation and the position of the invariant triangle in each case.

§2. The Pencil of Cubics, $x^3+y^3+z^3+6mxyz=0$.

The theory of the group of 216 collineations in the plane is so intimately related to the theory of a pencil of cubics through nine points of inflection, that a résumé of certain properties of such a pencil is a necessary preliminary to the study of the group.

If m is a variable parameter, the equation,

$$x^3+y^3+z^3+6mxyz=0, \qquad (1)$$

represents ∞^1 cubics having nine points of intersection which are points of inflection on all cubics of the pencil.

From any point P on a cubic C four tangents can be drawn to C exclusive of the tangent at P. The cross-ratio of these tangents is constant for all points on the curve and is different for different curves of the pencil. This cross-ratio k is absolutely unaltered by projection, and hence two cubics can not be linearly transformed into each other unless they have the same absolute invariant k. The value of k in terms of m is given by the equation

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$$\frac{(k^2-k+1)^3}{[(k+1)(k-2)(k-\frac{1}{2})]^2}=\frac{64m^3(m^3-1)^3}{(8m^6+20m^3-1)^2}=\phi(k). \qquad (2)$$

For any given value of k this is an equation of the twelfth degree in m; hence there are twelve cubics in the pencil, all having the same cross-ratio k. Given any cubic of the pencil it can be projected into itself and into only eleven other cubics of the pencil.

Expanding equation (2) we have

$$64(1-\phi)m^{12}-64(3+5\phi)m^9+192(1-2\phi)m^6-8(8-5\phi)m^3-\phi=0. \qquad (3)$$

The solution of this equation depends upon that of a quartic; its roots may be written m_i, αm_i, $\alpha^2 m_i$, $(i=1; 2, 3, 4)$ and $\alpha^3=1$. Hence our set of twelve is composed of four sub-divisions of three cubics each.

For certain special values of k our system of twelve cubics reduces to a smaller number. Thus when $k=-\alpha$ or $-\alpha^2$ we have $m=0, 1, \alpha, \alpha^2$; here the three cubics of each sub-division have coincided and our twelve cubics have reduced to four. These four cubics are called the *equianharmonic* cubics of the pencil. Their equations are

$$\begin{aligned}
&(1)\quad x^3+y^3+z^3=0,\\
&(2)\quad x^3+y^3+z^3+6xyz=0,\\
&(3)\quad x^3+y^3+z^3+6\alpha xyz=0,\\
&(4)\quad x^3+y^3+z^3+6\alpha^2 xyz=0.
\end{aligned} \qquad (4)$$

When $k=-1, 2, \frac{1}{2}$, the twelve values of m reduce to six; viz:

$$m=\frac{-1\pm\sqrt{3}}{2},\ \alpha\left(\frac{-1\pm\sqrt{3}}{2}\right),\ \alpha^2\left(\frac{-1\pm\sqrt{3}}{2}\right). \qquad (4a)$$

These six cubics are called the *harmonic* cubics of the pencil.

When $k=1, 0, \infty$, we have $m=\infty, -\frac{1}{2}, -\frac{1}{2}\alpha, -\frac{1}{2}\alpha^2$. These four cubics are characterized by the common property that each of them breaks up into three linear factors. Thus

$$\begin{aligned}
&(1)\ xyz=0,\\
&(2)\ x^3+y^3+z^3-3xyz=(x+y+z)(x+\alpha y+\alpha^2 z)(x+\alpha^2 y+\alpha z)=0,\\
&(3)\ x^3+y^3+z^3-3\alpha xyz=(\alpha x+y+z)(x+\alpha y+z)(x+y+\alpha z)=0,\\
&(4)\ x^3+y^3+z^3-3\alpha^2 xyz=(\alpha^2 x+y+z)(x+\alpha^2 y+z)(x+y+\alpha^2 z)=0.
\end{aligned} \qquad (5)$$

Each of these degenerate cubics consists of three straight lines which form a triangle, one of them being the triangle of reference. They are the inflectional triangles of the pencil of cubics.

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Between these four degenerate cubics and the four equianharmonic cubics there exists a very simple relation. Each equianharmonic cubic is gotten by taking the sum of the cubes of the linear factors of the corresponding degenerate cubic. Thus, for example, we have

$$3(x^3+y^3+z^3+6xyz)=(x+y+z)^3+(x+\alpha y+\alpha^2 z)^3 +(x+\alpha^2 y+\alpha x)^3. \qquad (6)$$

The coördinates of the nine points of inflection of the pencil of cubics is best found by eliminating between $x^3+y^3+z^3=0$ and $xyz=0$. They are as follows:

$$\begin{array}{lll} (1)\ 0,\ 1,\ -1; & (2)\ 0,\ \alpha,\ -1; & (3)\ 0,\ 1,\ -\alpha; \\ (4)\ -1,\ 0,\ 1; & (5)\ -1,\ 0,\ \alpha; & (6)\ -\alpha,\ 0,\ 1; \\ (7)\ 1,\ -1,\ 0; & (8)\ \alpha,\ -1,\ 0; & (9)\ 1,\ -\alpha,\ 0. \end{array} \qquad (7)$$

The harmonic polars of these nine points of inflection are given by the following equations:

$$\begin{array}{lll} (1)\ y-z=0, & (2)\ \alpha^2 y-z=0, & (3)\ \alpha y-z=0, \\ (4)\ z-x=0, & (5)\ \alpha^2 z-x=0, & (6)\ \alpha z-x=0, \\ (7)\ x-y=0, & (8)\ \alpha^2 x-y=0, & (9)\ \alpha x-y=0. \end{array} \qquad (8)$$

Each of the inflectional triangles intersect the pencil of cubics in the same nine points; hence the nine points of inflection lie three by three on twelve right lines. Each harmonic polar passes through a vertex of each of the four inflectional triangles; hence the twelve vertices of the inflectional triangles lie four by four on nine right lines.

The vertices of the four inflectional triangles may be designated by A_i, B_i, C_i, $(i=1, 2, 3, 4)$. The coördinates of these twelve points are as follows:

$$1.\begin{cases} 1,\ 0,\ 0, \\ 0,\ 1,\ 0, \\ 0,\ 0,\ 1. \end{cases} \quad 2.\begin{cases} 1,\ 1,\ 1, \\ 1,\ \alpha^2,\ \alpha, \\ 1,\ \alpha,\ \alpha^2. \end{cases} \quad 3.\begin{cases} \alpha^2,\ 1,\ 1, \\ 1,\ \alpha^2,\ 1, \\ 1,\ 1,\ \alpha^2. \end{cases} \quad 4.\begin{cases} \alpha,\ 1,\ 1, \\ 1,\ \alpha,\ 1, \\ 1,\ 1,\ \alpha, \end{cases} \qquad (9)$$

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§3. The Group G_{216}.

It is a well known fact* in the theory of plane cubics that every non-singular cubic C can be projectively transformed into itself in eighteen different ways and that these eighteen collineations form a group G_{18} which also transforms into itself every cubic of the pencil $C+6kH=0$. We shall investigate this group in detail in the next section, but here we wish to make use of the generally known fact.

It was shown in §2 that a cubic C is one of a set of twelve cubics C_i ($i=1 \ldots 12$) which can be projectively transformed into one another. Since each cubic of the set may be transformed into itself in eighteen different ways, we infer that each cubic of the set may also be transformed into any other cubic of the set in eighteen different ways. If this be true, there are 12.18 transformations which leave invariant the set of twelve cubics. These 216 collineations form a group G_{216}.

The configuration of four equianharmonic cubics, four degenerate cubics and six harmonic cubics—shown in §2—is analogous to a tetrahedron which has four vertices, four faces and six edges. Accordingly the structure of the group G_{216} is analogous to the structure of the tetrahedron group G_{12}, which we assume as known. To the identical substitution in G_{12} corresponds the group G_{18} in G_{216}. To the four sub-groups G_3 in G_{12}, each leaving a vertex and opposite face invariant, correspond four sub-groups G_{54} in G_{216}, each leaving invariant a degenerate and an equianharmonic cubic. To the three sub-groups G_2 in G_{12}, each leaving invariant a pair of opposite edges, correspond three sub-groups G_{36} in G_{216}, each leaving invariant a pair of conjugate harmonic cubics. To the invariant sub-group G_4 in G_{12} corresponds an invariant sub-group G_{72} in G_{216}.

We shall now take up the study of these sub-groups of G_{216} and examine into their structure and determine the properties of the individual transformations found in them. We shall determine in particular the order and the invariant triangle of each transformation occurring in G_{216}.

§4. The Group G_{18}.

The harmonic polar l of a point of inflection I is characterized by the following property: Every line through I cuts the cubic C in two other points P and Q and l in L. The cross-ratio of

*Clebsch, Vorlesungen ueber Geometrie, I, S. 512.

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(ILPR)=—1. If, therefore, we set up a perspective transformation of order 2 having I for its vertex and l for its axis, it will transform C into itself.

Take the point of inflection (0, 1, —1) and its harmonic polar y—z=0; choose any two points on this line as (0, 1, 1) and (1, 1, 1). The single cross-ratio of this transformation is k=—1. The equations of the transformation may be written down by means of the following formulas:*

$$\rho x_1 = \begin{vmatrix} x & y & z & o \\ A & B & C & A \\ A_1 & B_1 & C_1 & kA_1 \\ A_2 & B_2 & C_2 & k'A_2 \end{vmatrix}; \quad \rho y_1 = \begin{vmatrix} x & y & z & o \\ A & B & C & B \\ A_1 & B_1 & C_1 & kB_1 \\ A_2 & B_2 & C_2 & k'B_2 \end{vmatrix};$$

$$\rho z_1 = \begin{vmatrix} x & y & z & o \\ A & B & C & C \\ A_1 & B_1 & C_1 & kC_1 \\ A_2 & B_2 & C_2 & k'C_2 \end{vmatrix}. \qquad (10)$$

Substituting in these formulas the above values of A, B, etc., and making both k and k′ equal to —1, these reduce to

$$\begin{aligned} x_1 &= x, \\ y_1 &= z, \\ z_1 &= y. \end{aligned} \qquad (11)$$

There are nine transformations, one for each point of inflection; they may all be written down by means of the same general formula. Three of them will be real and six imaginary. If we make any one of these nine substitutions in the equation of the pencil of cubics, we find that every cubic of the pencil is transformed into itself.

Again, let us take a transformation whose invariant triangle is the triangle of reference and whose cross-ratios are k and k′. Writing down the equations of this transformation by means of formulas (10) we find $\begin{cases} x_1 = x \\ y_1 = ky \\ z_1 = k'z. \end{cases}$ Making this substitution in the equation of the pencil of cubics we get

$$x^3 + k^3y^3 + k'^3z^3 + 6mkk'xyz = 0.$$

*K. U. Quarterly, vol. viii, pp. 45-66. I have recently found that these formulas were previously given in nearly the same form by Prof. Gabriele Torrelli in the *Rendiconti di Circolo Matematico di Palermo, Tome* viii, pp. 41-54.

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Every cubic of the pencil will be transformed into itself when $k^3=1$, $k'^3=1$, and $kk'=1$. These relations are satisfied by $k=\alpha$ and $k'=\alpha^2$ or by $k=\alpha^2$ and $k'=\alpha$. Thus we have two transformations

$$\begin{array}{lll} x_1=x & & x_1=x \\ y_1=\alpha y & \text{and} & y_1=\alpha^2 y \\ z_1=\alpha^2 z & & z_1=\alpha z \end{array} \qquad (12)$$

of this kind which transform every cubic of the pencil into itself. These are a pair of inverse transformations and each of period 3.

In like manner it may be shown that each of the other inflectional triangles is the invariant triangle of a pair of transformations of period 3, such that they transform every cubic of the pencil into itself. In this way we find eight transformations of this variety. The equations of these eight transformations may be written down by means of formulas (10), making use of the values given in (9). These equations are as follows, numbered according to the triangles:

$$1.\begin{cases} x_1=x, & x \\ y_1=\alpha y, & \alpha^2 y; \\ z_1=\alpha^2 z, & \alpha z \end{cases} \quad 2.\begin{cases} y, & z \\ z, & x; \\ x, & y \end{cases} \quad 3.\begin{cases} y, & z \\ \alpha z, & \alpha^2 x; \\ \alpha^2 x, & \alpha y \end{cases} \quad 4.\begin{cases} y, & z \\ \alpha^2 z, & \alpha x \\ \alpha x, & \alpha^2 y \end{cases}. \qquad (13)$$

These eight transformations, together with the nine perspective transformations given above, and the identical transformation constitute a group G_{18}, every transformation in which transforms every cubic of the pencil into itself. The fact that these eighteen transformations form a group may be verified by applying the test of forming all possible resultants. There are no other transformations possessing this property,

It is evident from the character of the transformations contained in G_{18} that the group contains four cyclic sub-groups of order 3 and nine cyclic sub-groups of order 2. G_{18} also contains a subgroup G_6 of order 6 and one G_9 of order 9. These are given as follows:

$$G_6 \begin{cases} x_1=x, & x, & z. & y, & y, & z, \\ y_1=y, & z, & y, & x, & z, & x, \\ z_1=z, & y, & x, & z, & x, & y, \end{cases} = G_3+3G_2. \qquad (14)$$

All transformations of this group are real; one is of order 1, three of order 2 and two of order 3. The group G_9 is as follows:

$$G_9 \begin{cases} x_1=x, & x, & x, & y, & z, & y, & z, & y, & z, \\ y_1=y, & \alpha y, & \alpha^2 y, & z, & x, & \alpha z, & \alpha^2 x, & \alpha^2 z, & \alpha x. \\ z_1=z, & \alpha^2 z, & \alpha z, & x, & y, & \alpha^2 x, & \alpha y, & \alpha x, & \alpha^2 y, \end{cases} = 4G_3.$$

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This group contains one transformation of order 1 and eight of order 3.

Theorem 1.—Every transformation of the group G_{18} transforms into itself every cubic of the pencil $C+6mH=0$, where H is the Hessian of C; G_{18} contains (1) one transformation of order 1, (2) nine transformations of order 2, (3) eight transformations of order 3. These are as follows:

(1). The identical transformation.

(2). Each of the nine points of inflection and its corresponding harmonic polar are the vertex and axis respectively of a perspective transformation of order 2.

(3). Each of the four inflectional triangles is the invariant triangle of a pair of inverse transformations of type I and order 3.

§5. The Group G_{54} (1).

As remarked above, the group G_{216} contains four sub-groups $G_{54}(i)$, (i=1, 2, 3, 4), one for each equianharmonic cubic. We begin with the most simple one, which has for invariant figure the triangle of reference xyz=0 and the cubic $x^3+y^3+z^3=0$. This group G_{54} contains, of course, the eighteen transformations of G_{18} and hence thirty-six other transformations which we must investigate.

Since $x^3+y^3+z^3$ is an invariant of our group it is evident that the group contains all transformations of the form of those contained in G_{18}, where x, y, and z are interchanged in all possible ways and combined with the coefficients α, α^2, α^3, in all possible ways which give rise to different transformations. We can readily write down a table of all such transformations, and we find that it contains just fifty-four transformations and no more. These, then, constitute the group G_{54}. The table is as follows, in which the number placed above each formula indicates the order of the transformation:

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1	3	3	3	3	3	3	3	3
$x_1=x,$	$x,$	$x,$	$\alpha^2x,$	$\alpha x,$	$x,$	$x,$	$x,$	x
$y_1=y,$	$\alpha y,$	$\alpha^2y,$	$y,$	$y,$	$\alpha^2y,$	$\alpha y,$	$y,$	y
$z_1=z,$	$\alpha^2y,$	$\alpha z,$	$z,$	$z,$	$z,$	$z,$	$\alpha^2z,$	αz
2	2	2	6	6	6	6	6	6
$x_1=x,$	$x,$	$x,$	$\alpha^2x,$	$\alpha x,$	$x,$	$x,$	$x,$	x
$y_1=z,$	$\alpha z,$	$\alpha^2z,$	$z,$	$z,$	$\alpha^2z,$	$\alpha z,$	$z,$	z
$z_1=y,$	$\alpha^2y,$	$\alpha y,$	$y,$	$y,$	$y,$	$y,$	$\alpha^2y,$	αy
2	2	2	6	6	6	6	6	6
$x_1=z,$	$z,$	$z,$	$\alpha^2z,$	$\alpha z,$	$z,$	$z,$	$z,$	z
$y_1=y,$	$\alpha y,$	$\alpha^2y,$	$y,$	$y,$	$\alpha^2y,$	$\alpha y,$	$y,$	y
$z_1=x,$	$\alpha^2x,$	$\alpha x,$	$x,$	$x,$	$x,$	$x,$	$\alpha^2x,$	αx
2	2	2	6	6	6	6	6	6
$x_1=y,$	$y,$	$y,$	$\alpha^2y,$	$\alpha y,$	$y,$	$y,$	$y,$	y
$y_1=x,$	$\alpha x,$	$\alpha^2x,$	$x,$	$x,$	$\alpha^2x,$	$\alpha x,$	$x,$	x
$z_1=z,$	$\alpha^2z,$	$\alpha z,$	$z,$	$z,$	$z,$	$z,$	$\alpha^2z,$	αz
3	3	3	3	3	3	3	3	3
$x_1=y,$	$y,$	$y,$	$\alpha^2y,$	$\alpha y,$	$y,$	$y,$	$y,$	y
$y_1=z,$	$\alpha z,$	$\alpha^2z,$	$z,$	$z,$	$\alpha^2z,$	$\alpha z,$	$z,$	z
$z_1=x,$	$\alpha^2x,$	$\alpha x,$	$x,$	$x,$	$x,$	$x,$	$\alpha^2x,$	αx
3	3	3	3	3	3	3	3	3
$x_1=z,$	$z,$	$z,$	$\alpha^2z,$	$\alpha z,$	$z,$	$z,$	$z,$	z
$y_1=x,$	$\alpha x,$	$\alpha^2x,$	$x,$	$x,$	$\alpha^2x,$	$\alpha x,$	$x,$	x
$z_1=y,$	$\alpha^2y,$	$\alpha y,$	$y,$	$y,$	$y,$	$y,$	$\alpha^2y,$	αy

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We observe that the eighteen transformations given in the first three columns of the table form the group G_{18} discussed above. We shall find that of the thirty-six remaining transformations eighteen are of order 3 and eighteen of order 6; we shall further find that there are two distinct varieties of these transformations of order 3.

We first consider the last six transformations of the first row of the table. Take first the transformation $\begin{cases} x_1 = \alpha^2 x \\ y_1 = y; \\ z_1 = z \end{cases}$ it evidently leaves invariant each side of the triangle of reference. It may also be written in the form $\begin{cases} x \\ \alpha y, \\ \alpha z \end{cases}$ from which we see that the cross-ratios along the sides y and z are each equal to α and that along x is unity. The transformation is, therefore, of type IV, the axis of invariant points being x=o; and the single invariant point or vertex being the point (1, o, o), the opposite vertex of the invariant triangle. This transformation is evidently of order 3; its inverse is also its square viz: $\begin{cases} \alpha x \\ y. \\ z \end{cases}$ In like manner it is seen that the two inverse transformations $\begin{cases} x, \\ \alpha^2 y, \\ z, \end{cases}$ $\begin{cases} x \\ \alpha y, \\ z \end{cases}$ are also of type IV and of order 3, the axis being y=o and the vertex being the opposite vertex of the triangle of reference. A similar results holds also for the pair $\begin{cases} x, \\ y, \\ \alpha^2 z, \end{cases}$ $\begin{cases} x \\ y. \\ \alpha z \end{cases}$ We have thus found six perspective transformations, each of order 3; these are easily identified with the last six transformations of the first row of the table.

We next consider the fourth transformation of the second row of the table, viz: $\begin{cases} \alpha^2 x \\ z. \\ y \end{cases}$ Calling it T we have,

$$T = \begin{matrix} \alpha^2 x, \\ y \end{matrix} \quad z, \quad T^2 = \begin{matrix} \alpha x, \\ z \end{matrix} \quad y, \quad T^3 = \begin{matrix} x, \\ y \end{matrix} \quad z, \quad T^4 = \begin{matrix} \alpha^2 x, \\ z \end{matrix} \quad y, \quad T^5 = \begin{matrix} \alpha x, \\ y \end{matrix} \quad z, \quad T^6 = \begin{matrix} x, \\ z \end{matrix} \quad y, = 1. \qquad (15)$$

The transformation T is therefore of order 6; T^2 and T^4 are of order 3 and T^3 is of order 2. T^2, T^3, T^4 have been studied above and their characteristics are already known.

T and its inverse T^5 are now to be investigated. The invariant

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triangle of T is found by putting x_1, y_1, and z_1 equal to x, y, and z respectively. We thus find that the sides of the invariant triangle are x=o, y−z=o, and y+z=o. Solving these equations we find the vertices of the invariant triangle to be A=(o,1,−1), B=(1,o,o), C=(o,1,1). Thus one vertex, A, of the invariant triangle is a point of inflection and the opposite side is its harmonic polar. One vertex of the inflectional triangle, xyz=o, lies on this harmonic polar, viz: (1,o,o); the opposite side, x=o, completes the invariant triangle. The position of the invariant triangle is thus completely determined.

The cross-ratios along the sides AB, BC, CA of the invariant triangle are respectively $-a^2$, a, -1. This may be verified by writing down the cross-ratios of the first six powers of T, assuming T to be given by $-a^2$, a, -1. Thus

$$\begin{array}{lccc} & \text{AB} & \text{BC} & \text{CA} \\ T=-a^2, & & a, & -1; \\ T^2=a, & & a^2, & 1; \\ T^3=-1, & & 1, & -1; \\ T^4=a^2, & & a, & 1; \\ T^5=-a, & & a^2, & -1; \\ T^6=1, & & 1, & 1. \end{array} \qquad (16)$$

T^2 and T^4 are thus shown to be transformations of type IV and order 3, having an identical transformation along the side CA. T^3 is of type IV and order 2, having an identical transformation along BC.

The transformation T may be written down by means of formulas (10) as follows:

$$\rho x_1 = \begin{vmatrix} x & y & z & o \\ o & 1 & -1 & o \\ 1 & o & o & -a^2 \\ o & 1 & 1 & o \end{vmatrix}; \quad \rho y_1 = \begin{vmatrix} x & y & z & o \\ o & 1 & -1 & 1 \\ 1 & o & o & o \\ o & 1 & 1 & -1 \end{vmatrix}$$

$$\rho z_1 = \begin{vmatrix} x & y & z & o \\ o & 1 & -1 & -1 \\ 1 & o & o & o \\ o & 1 & 1 & -1 \end{vmatrix}.$$

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Hence we have $\rho x_1 = -2a^2 x$, $\rho y_1 = -2z$, $\rho z_1 = -2y$; or $\begin{cases} x_1 = a^2 x \\ y_1 = z. \\ z_1 = y \end{cases}$

We have seen how the two transformations T and T^5 are related to the point of inflection A. In like manner there are two transformations of order 6 related in the same way to each of the nine points of inflection. We have thus eighteen transformations of order 6. Their equations may readily be found from their known invariant triangles by means of formulas (10). These eighteen transformations are all given in rows 2, 3, and 4, of the table.

There still remain to be investigated the twelve transformations found in the last six places in rows 5 and 6. Take, for example, $\begin{cases} x_1 = a^2 y \\ y_1 = z \\ z_1 = x \end{cases}$ and denote it by S. Taking the powers of S we find

$$S = \begin{matrix} a^2 y, \\ z, \\ x, \end{matrix} \quad S^2 = \begin{matrix} a^2 z, \\ x, \\ a^2 y, \end{matrix} \quad \text{or} \quad \begin{matrix} z, \\ ax, \\ y, \end{matrix} \quad \begin{matrix} a^2 x \\ a^2 y = 1, \\ a^2 z \end{matrix} \quad S^3 = a^2 y = 1,$$

S and S^2 are thus of order 3. We proceed to find the vertices of the invariant triangle of S by solving the equations $\begin{matrix} x = a^2 y \\ y = z. \\ z = x \end{matrix}$ We find the coördinates of the invariant points to be $A = (1, \lambda^8, \lambda^4)$, $B = (1, \lambda^5, \lambda^7)$, $C = (1, \lambda^2, \lambda)$, where λ is an irreducible 9th root of unity. Since $1 + \lambda^6 + \lambda^3 = 0$, it follows that these points all lie on the cubic $x^3 + y^3 + z^3 = 0$. It may easily be verified that the tangent to this cubic A cuts the cubic again at B; the tangent at B cuts again at C; and the tangent at C cuts the cubic again at A. Hence the cubic is both inscribed and circumscribed to the triangle ABC.

In order to determine the number of such triangles both inscribing and circumscribing the cubic, $x^3 + y^3 + z^3 = 0$, we write down the tangent at the point x', y', z'; viz: $xx'^2 + yy'^2 + zz'^2 = 0$. If this passes through the point x'', y'', z'', we have $x''x'^2 + y''y'^2 + z''z'^2 = 0$; and similar results for the other points. Thus we have six equations, viz:

$$\begin{aligned} &x''x'^2 + y''y'^2 + z''z'^2 = 0, && x'^3 + y'^3 + z'^3 = 0, \\ &x'''x''^2 + y'''y''^2 + z'''z''^2 = 0, && x''^3 + y''^3 + z''^3 = 0, \\ &x'x'''^2 + y'y'''^2 + z'z'''^2 = 0, && x'''^3 + y'''^3 + z'''^3 = 0, \end{aligned} \qquad (17)$$

from which to determine the coördinates of the invariant points. These equations have eighteen solutions; hence there are six such triangles. The coördinates of these eighteen points are as follows:

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$$\begin{Bmatrix} 1, & \lambda^6, & \lambda^4 \\ 1, & \lambda^5, & \lambda^7 \\ 1, & \lambda^2, & \lambda \end{Bmatrix}, \quad \begin{Bmatrix} 1, & \lambda^7, & \lambda^8 \\ 1, & \lambda, & \lambda^5 \\ 1, & \lambda^4, & \lambda^2 \end{Bmatrix}, \quad \begin{Bmatrix} 1, & \lambda^5, & \lambda^4 \\ 1, & \lambda^2, & \lambda^7 \\ 1, & \lambda^8, & \lambda \end{Bmatrix},$$

$$\begin{Bmatrix} 1, & \lambda, & \lambda^8 \\ 1, & \lambda^4, & \lambda^5 \\ 1, & \lambda^7, & \lambda^2 \end{Bmatrix}, \quad \begin{Bmatrix} 1, & \lambda^5, & \lambda \\ 1, & \lambda^2, & \lambda^4 \\ 1, & \lambda^8, & \lambda^7 \end{Bmatrix}, \quad \begin{Bmatrix} 1, & \lambda, & \lambda^2 \\ 1, & \lambda^4, & \lambda^8 \\ 1, & \lambda^7, & \lambda^5 \end{Bmatrix}.$$

Each of these triangles is the invariant triangle of two transformations of order 3. Thus we have twelve transformations of this variety. The equations of these twelve transformations may be written down by means of formulas (10). We give one example:

$$\rho x_1 = \begin{vmatrix} x & y & z & o \\ 1 & \lambda & \lambda^2 & 1 \\ 1 & \lambda^7 & \lambda^5 & a \\ 1 & \lambda^4 & \lambda^8 & a^2 \end{vmatrix}, \quad \rho y_1 = \begin{vmatrix} x & y & z & o \\ 1 & \lambda & \lambda^2 & \lambda \\ 1 & \lambda^7 & \lambda^5 & \lambda^7 a \\ 1 & \lambda^4 & \lambda^8 & \lambda^4 a^2 \end{vmatrix},$$

$$\rho z_1 = \begin{vmatrix} x & y & z & o \\ 1 & \lambda & \lambda^2 & \lambda \\ 1 & \lambda^7 & \lambda^5 & \lambda^5 a \\ 1 & \lambda^4 & \lambda^8 & \lambda^8 a^2 \end{vmatrix}.$$

These reduce to $\rho x_1 = 3\lambda(a - a^2)z$, $\rho y_1 = 3\lambda^4(a - a^2)x$, $\rho z_1 = 3\lambda^4(a - a^2)y$

or $\begin{cases} x_1 = a^2 z \\ y_1 = x. \\ z_1 = y \end{cases}$ The eleven others are obtained in like manner.

The following sub-groups of G_{54} may be noted: G_{18} is an invariant sub-group; the nine transformations in the first row of the table form a group G_9. This group leaves invariant all three sides of the triangle $xyz=0$. The first and second rows of the table constitute a group xG_{18}, which leaves invariant the side $x=0$. In like manner the first and third rows and the first and fourth rows form groups yG_{18} and zG_{18}, whose invariants are respectively $y=0$ and $z=0$. Rows 1, 5 and 6 form a group G_{27}.

§6. The Groups $G_{54}(i)$ $(i=2,3,4)$.

Having determined the structure and properties of the group G_{54} (1) we can readily find from this the structure and properties of its equivalent groups $G_{54}(i)$ $(i=2,3,4)$. We shall first confine our attention to the group $G_{54}(2)$.

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The invariants of this group are the cubic and triangle (2) of equations (4) and (5) as follows:

$$(2) \qquad x^3+y^3+z^3+6xyz=0$$

and

$$(2) \qquad (x+y+z)(x+\alpha y+\alpha^2 z)(x+\alpha^2 y+\alpha z)=0. \qquad (18)$$

The triangle and cubic (1) are transformed into triangle and cubic (2) by the transformation.

$$T\equiv\begin{matrix} x_1=z+y+z \\ y_1=x+\alpha y+\alpha^2 x \\ z_1=x+\alpha^2 y+\alpha z. \end{matrix} \qquad (19)$$

Hence the group G_{54} (1) is transformed into G_{54} (2) by means of the transformation T. Thus we have $TS_1T^{-1}=S_2$, where S_2 is a transformation of G_{54} (2). By this operation the invariant points of the individual transformations in G_{54} (1) are transformed into those of G_{54} (2). We shall now verify this for a few cases.

The eighteen transformations of G_{18} are contained in G_{54} (2) and hence we expect that the operations symbolized by $TG_{18}T^{-1}$ will give us again G_{18}. The transformation $S=\begin{cases} x \\ z \\ y \end{cases}$ leaves invariant the point of inflection (0, 1, —1) and its harmonic polar y—z=0. The coördinates (0, 1, —1) substituted in T give again (0, 1, —1). From the form of T we have y—z=(α—α²)(y—z). The operation TS_1T^{-1} gives S_1 as may easily be verified.

Again take the transformation $S=\begin{cases} x \\ \alpha y \\ \alpha^2 z \end{cases}$ whose invariant triangle is $\begin{cases} 1,0,0 \\ 0,1.0. \\ 0,0,1 \end{cases}$ The operation TS_1T^{-1} gives $S'\begin{cases} y \\ z; \\ x \end{cases}$ and the above coördinates substituted in T gives $\begin{cases} 1,1,1 \\ 1,\alpha,\alpha^2 \\ 1,\alpha^2,\alpha \end{cases}$ as the invariant triangle of the new transformation. This is as it should be (see equation 9). In this way it may be verified in detail that G_{18} is an invariant sub-group of G_{54} (1).

The perspective transformation $\begin{cases} \alpha^2 x \\ y, \\ z \end{cases}$ leaving invariant a vertex and opposite side of triangle (1), is transformed by T into a new perspective transformation, leaving invariant a vertex and opposite

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side of triangle (2). The vertex (1,0,0) and opposite side $x=0$ of triangle (1) are transformed by T into (1,1,1) and $x+y+z=0$, vertex and opposite side of triangle (2). Transforming this perspective transformation by T we get

$$TST^{-1} \equiv \begin{aligned} \rho x_1 &= \alpha x + y + z \\ \rho y_1 &= x + \alpha y + z \\ \rho z_1 &= x + y + \alpha x, \end{aligned} \qquad (20)$$

which is likewise a perspective transformation of order 3.

We next take the transformation designated by T in §5, viz: $\begin{cases} \alpha^2 x \\ z. \\ y \end{cases}$ Call it S_6 for convenience. Its invariant triangle was found to be $\begin{cases} 0,1,-1 \\ 1,0,0. \\ 0,1,1 \end{cases}$ Substituting these values in T we get $\begin{cases} 0,1,-1 \\ 1,1,1 \\ 2,1,-1 \end{cases}$ as the vertices of the invariant triangle of the transformation TS_6T^{-1}. Performing the operation indicated by TS_6T^{-1} we get

$$TS_6T^{-1} \equiv \begin{aligned} \rho x_1 &= \alpha x + y + z, \\ \rho y_1 &= x + y + \alpha z, \\ \rho z_1 &= x + \alpha y + z, \end{aligned} \qquad (21)$$

which is accordingly the transformation in G_{54} (2) corresponding to S_6 in G_{54} (1). It is easy to verify that TS_6T^{-1} is of order 6 and that its invariant triangle is $\begin{cases} 0,1,-1 \\ 1,1,1. \\ 2,-1,-1 \end{cases}$ It should be remarked that the point (0,1,−1) is a point of inflection, (1,1,1) the vertex of the triangle (2) which lies on the polar of (0,1,−1), and (2,−1,−1) is the intersection of the harmonic polar and the side of triangle (2) opposite (1,1,1). (See the discussion of the transformation S_6 in §5.) In a similar manner the equations of the other seventeen transformations of order 6 in G_{54} (2) may be written down and their invariant triangles determined.

We come finally to the consideration of the twelve transformations in G_{54} (2), corresponding to those in G_{54} (1) whose invariant triangles are both inscribed and circumscribed to the cubic (1). Take, for example, the transformation $S_3 = \begin{cases} \alpha^2 y \\ z, \\ x \end{cases}$ the coördinates of whose invariant points are $\begin{cases} 1,\lambda^8,\lambda^4 \\ 1,\lambda^5,\lambda^7. \\ 1,\lambda^2,\lambda \end{cases}$ (See §5.) The transformation TS_3T^{-1} is found to be

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$$TST^{-1} \equiv \begin{aligned} \rho x_1 &= z + \alpha y + z, \\ \rho y_1 &= \alpha^2 x + \alpha^2 y + z, \\ \rho z_1 &= \alpha^2 x + \alpha y + \alpha z. \end{aligned} \tag{22}$$

The coördinates of the vertices of the invariant triangle of TS_3T^{-1} are found by substituting in T the coördinates of those of S_3. We thus find

$$\begin{cases} 1+\lambda^6+\lambda^4, & 1+\lambda^2+\lambda, & 1+\lambda^5+\lambda^7, \\ 1+\lambda^5+\lambda^7, & 1+\lambda^8+\lambda^4, & 1+\lambda^2+\lambda, \\ 1+\lambda^2+\lambda, & 1+\lambda^5+\lambda^7, & 1+\lambda^8+\lambda^4, \end{cases}$$

as the vertices of the invariant triangle of TS_3T^{-1}. This triangle is both inscribed and circumscribed to the cubic (2). There are six such triangles and their vertices may be found in a manner similar to the above. The equations of the twelve transformations corresponding to these triangles may be obtained by transforming the twelve corresponding transformations in G_{54} (1) by means of T.

This completes the discussion of the group G_{54} (2). The groups G_{54} (3) and G_{54} (4) may be treated in a similar manner. The invariant triangle $xyz=0$ of G_{54} (1) is transformed into the invariant triangle of G_{54} (3) by the transformation

$$T_1 \equiv \begin{aligned} \rho x_1 &= \alpha x + y + z, \\ \rho y_1 &= x + \alpha y + z, \\ \rho z_1 &= x + y + \alpha z, \end{aligned} \tag{23}$$

and into the invariant triangle of G_{54} (4) by the transformation

$$T_2 \equiv \begin{aligned} \rho x_1 &= \alpha^2 x + y + z, \\ \rho y_1 &= x + \alpha^2 y + z, \\ \rho z_1 &= x + y + \alpha^2 z. \end{aligned} \tag{24}$$

Hence, if we change T into T_1 in the above discussion, all of the results thus obtained hold true for the group G_{54} (3); replacing T by T_2 we get the corresponding results for G_{54} (4). These four groups $G_{54}(i)$ $(i=1,2,3,4)$ contain $4.36+18=162$ different transformations.

Theorem 2.—Every transformation of the group $G_{36}(i)$ $(i=1,2,3,4)$ transforms into itself the inflectional triangle i and its corresponding equianharmonic cubic. $G_{36}(i)$ contains (1) the eighteen transformations of G_{18}, (2) six of type IV and order 3, (3) twelve of type I and order 3, eighteen of type I and order 6.

(2). Each vertex and opposite side of the inflectional triangle i

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are the vertex and axis respectively of a pair of inverse perspective transformations of order 3.

(3). Each of the six triangles both inscribed and circumscribed to the equianharmonic cubic i is the invariant triangle of a pair of inverse transformations of type I and order 3.

(4). Each of the nine triangles, k, (k=1 . . 9), described below, is the invariant triangle of a pair of inverse transformations of type I and order 6. A point of inflection k and its corresponding harmonic polar form one vertex and the opposite side of the invariant triangle; that vertex of the inflectional triangle i which is on this harmonic polar and that side of the triangle i which passes through the point of inflection k complete the invariant triangle.

§7. The Group G_{36} (1).

It was pointed out in §2 that the group G_{216} contains three equivalent sub-groups $G_{36}(j)$ (j=1,2,3), one corresponding to each pair of harmonic cubics in the pencil C+6kH=0. We first take up the group G_{36} (1), which leaves invariant the pair of cubics given by $m=\frac{-1\pm\sqrt{3}}{2}$ in the pencil $x^3+y^3z^3+6mxyz=0$.

We learned in §6 that the transformation

$$T\equiv\begin{cases}\rho x_1=x+y+z,\\ \rho y_1=z+\alpha y+\alpha^2 z,\\ \rho z_1=x+\alpha^2 y+\alpha z,\end{cases}$$

transforms the cubic $x^3+y^3+z^3=0$ into $x^3+y^3+z^3+6xyz=0$. If we make the substitution T in cubic (2) we find that it is transformed into (1); thus T interchanges the two equianharmonic cubics (1) and (2). It may also be verified that T interchanges the equianharmonic cubics (3) and (4). If, however, we make the substitution T in the pair of harmonic cubics

$$x^3+y^3+z^3+6mxyz=0, \qquad \left(m=\frac{-1\pm\sqrt{3}}{2}\right) \qquad (25)$$

we find that both of these cubics remain invariant. Thus T is a transformation belonging to the group $G_{36}(j)$, since it leaves invariant a pair of harmonic cubics.

Since T interchanges the equianharmonic cubics (1) and (2), T^2 must leave both of them invariant; hence T^2 is a transformation of the group G_{18}. We readily find $T^2=\begin{cases}x\\ z.\\ y\end{cases}$ We found in §4 that

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the transformation $\begin{cases} x \\ z \\ y \end{cases}$ is a perspective transformation of order 2; hence T is of order 4. T^3 is the inverse of T and is given by

$$T^3 = \begin{aligned} \rho x_1 &= x+y+z, \\ \rho y_1 &= x+\alpha^2 y+z, \\ \rho z_1 &= x+\alpha y+\alpha^2 z. \end{aligned} \qquad (26)$$

The vertex of the perspective transformation T^3 is the point of inflection A=(0,1,−1), and its axis is the harmonic polar of A, viz: y—z=0. Hence the other two invariant points B and C of T are on the line y—z=0. To find B and C we proceed as follows: Assume the coördinates of B to be (1,a,a); these satisfy y—z=0. Substitute these assumed coördinates of B in T and we must get again (1,a,a). Substituting we have

$$\begin{aligned} \rho x_1 &= 1+2a \\ \rho y_1 &= 1+a\alpha+a\alpha^2; \\ \rho z_1 &= 1+a\alpha^2+a\alpha \end{aligned} \qquad (27)$$

whence $\frac{1+2a}{1+a\alpha+a\alpha^2}=a$; solving for a we find $a=\frac{-1\pm\sqrt{3}}{2}$. Since we have found two values of a, it follows that we have the coördinates of both B and C. The invariant triangle of T is therefore given by $\begin{cases} 0, & 1, & -1 \\ 1, & \frac{-1+\sqrt{3}}{2}, & \frac{-1+\sqrt{3}}{2} \\ 1, & \frac{-1-\sqrt{3}}{2}, & \frac{-1-\sqrt{3}}{2} \end{cases}$. We may check the correctness of this result by using these values in formulas (10) along with k=i and k′=—i. We deduce thereby the transformation T.

The invariant points B and C are somehow related to the harmonic cubics of equation (25). We readily find that the point B is on the cubic

$$a\equiv x^3+y^3+z^3+6\left(\frac{-1-\sqrt{3}}{2}\right)xyz=,$$

and C is on the cubic

$$b\equiv x^3+y^3+z^3+6\left(\frac{-1+\sqrt{3}}{2}\right)xyz=0.$$

The six points in which the line y—z=0 cuts the two cubics a and

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b are in involution, and the invariant points B and C, one on each cubic, constitute the double points of the involution. The other two points on each cubic form pairs of points in the involution. The transformation T^3 evidently has the same invariant triangle as T.

We have now seen how the two transformations T and T^3 of order 4 are related to the point of inflection A and the pair of harmonic cubics a and b. It may be shown in the same way that there are two transformations of order 4 related in the same manner to each of the nine points of inflection and the cubics a and b. The invariant triangle having one vertex at any given point of inflection may easily be found and the corresponding transformations written down by means of formulas (10). In this way we see that there are eighteen transformations of order 4, each of which leaves invariant the pair of harmonic cubics a and b. These eighteen transformations, together with G_{18}, constitute the group G_{36} which we set out to investigate.

§8. The Groups G_{36} (2) and G_{36} (3)

The three groups $G_{36}(j)$ $(j=1,2,3)$ are eqivalent sub-groups of G_{216} and hence are similar in structure. Knowing the structure of G_{36} (1) we infer at once the structure of the other two groups. Take the group whose invariants are the pair of harmonic cubics

$$c\equiv x^3+y^3+z^3+6\alpha\left(\frac{-1+\sqrt{3}}{2}\right)xyz=0,$$

and

$$d\equiv x^3+y^3+z^3+6\alpha\left(\frac{-1-\sqrt{3}}{2}\right)xyz=0.$$

The eighteen transformations of order 4 are distributed so that two of them correspond to each point of inflection. The invariant triangle of such a pair of transformations consists of a point of inflection A and the pair of double points in the involution which the harmonic polar of A cuts from the two cubics c and d.

We shall here follow out one example. Take the point of inflection A=(0,1,−1); its harmonic polar is y−z=0. The double points of the involution cut from the cubics c and d by y−z=0 are found to be B=1, $\alpha\left(\frac{-1+\sqrt{3}}{2}\right)$, $\alpha\left(\frac{-1+\sqrt{3}}{2}\right)$ and

=1, $\alpha\left(\frac{-1-\sqrt{3}}{2}\right)$, $\alpha\left(\frac{-1-\sqrt{3}}{2}\right)$.

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B is on the curve d and C on c. By means of formulas (10) we find the corresponding inverse pair of transformations to be

$$\begin{cases} \rho x_1 = \alpha^2 x + y + z \\ \rho y_1 = \alpha x + y + \alpha z \\ \rho z_1 = \alpha x + \alpha y + z \end{cases} \quad \text{and} \quad \begin{cases} \alpha^2 x + y + z \\ \alpha x + \alpha y + z \\ \alpha x + y + \alpha z. \end{cases} \tag{28}$$

All other transformations of order 4 in this group may be obtained in the same way.

The group G_{36} (2) may also be obtained from G_{36} (1) by transforming the latter by some transformation that changes the harmonic cubics a and b into c and d. $S \equiv \begin{cases} \alpha x \\ y \\ z \end{cases}$ is such a transformation. By substituting the coördinates of the vertices of the invariant triangles of G_{36} (1) in S we obtain those of G_{36} (2). The operation STS^{-1} applied to the transformations of G_{36} (1) give those of G_{36} (2).

The group G_{36} (3) may be obtained in the same way from G_{36} (1) by using the transformation $\begin{cases} \alpha^2 x \\ y \\ z \end{cases}$ with the transformations of G_{36} (1); a detailed discussion is not necessary.

Theorem 3.—Every transformation of the group $G_{36}(j)$ (j=1,2,3) leaves invariant a pair of harmonic cubics j; $G_{36}(j)$ contains the eighteen transformations of G_{18} and also eighteen others of type I and order 4. Each of the nine triangles formed by the point of inflection k and the double points of the involution which the harmonic polar of k cuts from the pair of harmonic cubics j is the invariant triangle of a pair of inverse transformations of type I and order 4.

§9. The Group G_{72}.

The three groups $G_{36}(j)$ (j=1,2,3) contains in all fifty-four transformations of order 4. These, together with the eighteen of the group G_{18}, constitute the group G_{72}. This group G_{72} contains therefore no new transformations; accordingly we shall not consider this group at length. These fifty-four transformations of order 4, added to the 162 determined above and found in the four groups $G_{54}(i)$ (i=1,2,3,4), give the 216 transformations of G_{216}.

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§10. Conclusion.

The transformations contained in the group G_{216} may be divided into three classes as follows: (1) the eighteen transformations belonging to the Group G_{18}; (2) the 144 transformation in the four groups $G_{54}(i)$ and not belonging to G_{18}; (3) the fifty-four transformations in G_{72} not belonging to G_{18}.

The cubics of the pencil $C+6kH=0$ are distributed into sets of twelve each, such that each set of twelve cubics is an invariant of the group G_{216}. Each set of twelve is divided into four sub-sets of three cubics each; thus: m_i, αm_i, $\alpha^2 m_i$, $(i=1,2,3,4)$ where the m's are the roots of equation (3).

The effect of a transformation of the first class is to transform every cubic of the pencil $C+6kH=0$ into itself. The effect of a transformation of the second class is to cyclically interchange the three cubics of one sub-set in each set of twelve and to cyclically interchange the other three sub-sets. As a special case of this one of the equianharmonic cubics is invariant and the other three are cyclically interchanged; also one of the inflectional triangles is invariant and the other three is cyclically interchanged. The three pairs of harmonic cubics are cyclically interchanged by a transformation of this class. A transformation of the third class interchanges by twos the four equianharmonic cubics and also interchanges by twos the four inflectional triangles. It leaves invariant one pair of harmonic cubics and interchanges the other two pairs.

Since the Hessian of a cubic is a covariant of the cubic, every transformation that leaves a cubic invariant must leave its Hessian also invariant. Thus every transformation of the first class leaves both cubic and Hessian invariant. The Hessian of an equianharmonic cubic is its corresponding inflectional triangle. These are invariant together under a transformation of the second class. The Hessian of a harmonic cubic is the other harmonic cubic of the same pair; these are invariant together under a transformation of the third class.

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PLATE I.

Fig. 1. *Taenopteris newberriana(?)*. Natural size. No. 5000. Univ. of Kans.

Fig. 1a. Scars, fungi(?). On the rachis of *T. newberriana(?)*. Times 3. No. 5000.

Fig. 2. Venation of *T. newberriana(?)*. Times 2. No. 5001.

Fig. 3. Sporangia, like bodies between the veins of same. Times 2. No. 5003.

Fig. 4. One of the bodies showing slit on the side. Enlarged. Times 30.

Fig. 5. Another with slit across the top. Times 30.

Fig. 6. Bodies between the veins of *T. coriacea*. Times 2. Taken from specimen Fig. 3, Plate IV.

Fig. 7. *T. newberriana(??)* Natural size. No. 5006.

Fig. 8. Venation of *T. coriacea* near the base of the frond. Times 2.

Fig. 9. Venation of the same species near the apex. Times 2.

Fig. 10. Sporangium(?) of *T. coriacea*. Times 30. From Fig. 3, Plate IV.

Fig. 11. Same, showing slit across the top. Times 30.

Fig. 12. Cavity from which the sporangium(?) has been removed. Times 30.

Fig. 13. Venation of T. *newberriana(?)* near the apex. Times 2. From Fig. 1, Plate I.

Fig. 14. *T.* sp. Natural size. No. 5008.

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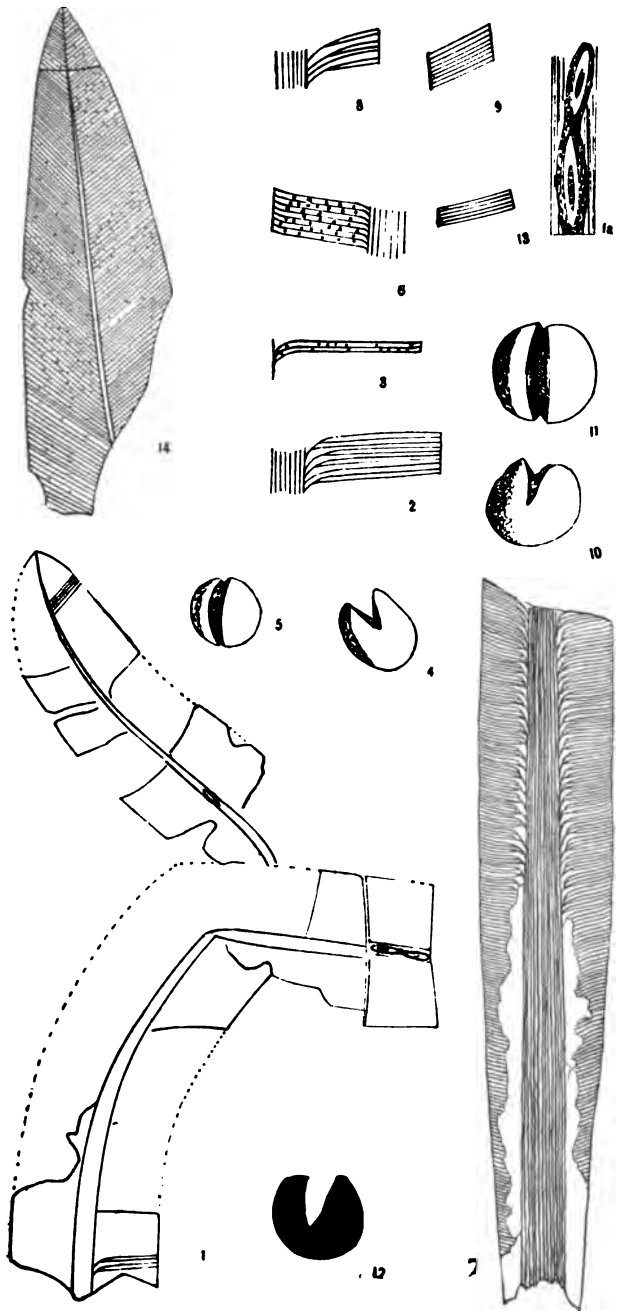

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PLATE II.

Fig. 1. *Taeniopteris coriacea.* Natural size. No. 5022.

Fig. 2. Same species, showing fungi like scars on the lamina. Natural size. No. 5023.

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PLATE III.

Fig. 1. *T. coriacea* with scars, fungi(?) on the rachis. No. 5002.

Fig. 2. Same species, apex of the front. No. 5024.

Fig. 3. *T, coriacea* var. *linearis* var. n. No. 5004.

Fig. 4. Same. No. 5005.

All natural size.

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PLATE IV.

Fig. 1. *Taenioptaris coriacea.* A small frond, slightly reduced. No. 5025.

Fig. 2. *T. newberriana(?).* Fragment showing two scars on the rachis and a smaller one in the edge on the lamina. No. 5009.

Fig. 3. Fragment of a small frond of *T. coriacea,* with oval bodies between the veins and casts of the same. No. 5026.

Fig. 4. *T. newberriana(?)* near the base of the frond. No. 5010. Figures 2, 3, and 4, natural size.

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THE

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SERIES A.—SCIENCE AND MATHEMATICS.

CONTENTS:

I.—ON THE GROUP AND SUBGROUPS OF REAL COLLINEATIONS LEAVING A TETRAHEDRON INVARIANT, ... *H. B. Newson.*

II.—THE DIMORPHISM OF CAMBARUS, I, ... *J. Arthur Harris.*

III.—SPERMATOGENESIS OF THE MYRIAPODS, I, . . . *M. W. Blackman.*

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KANSAS UNIVERSITY QUARTERLY.

VOL. X, No. 2. APRIL, 1901. SERIES A.

ON THE GROUP AND SUBGROUPS OF REAL COLLINEATIONS LEAVING A TETRAHEDRON INVARIANT.

BY H. B. NEWSON.

THE real collineations in space which have the same invariant tretrahedron are mostly of type I;* the exceptions will be noted later. There are three cases to be considered: (1) The tetrahedron is real in all of its parts; (2) the tretrahedron has two real and two conjugate imaginary vertices, two real and two conjugate imaginary faces, two real and two pairs of conjugate imaginary edges; (3) all the vertices and faces are imaginary in conjugate pairs, while two of the edges are real. These three cases must be treated separately.

§1. THE GROUP WITH REAL INVARIANT TETRAHEDRON AND ITS ONE-PARAMETER SUBGROUPS.

The Group hG_3 ($ABCD$).—Let T be a collineation of type I, leaving invariant a real tetrahedron (ABCD). T is fully determined by the positions of the four points A, B, C, D, and three constant cross-ratios k, k′, k″. Starting from the vertex A we take for k, k′, k″ the cross-ratios along the lines AB, AC, and AD, respectively. The quantities k, k′ and k″ are independent of one another, and vary independently, thus giving us ∞^3 different collineations, all leaving the four points A, B, C, D, separately invariant. These collineations or projective transformations form a three-parameter group hG_3 (ABCD), the parameters being k, k′, k″.

THEOREM 1. The aggregate of all collineations of type I having the same invariant tetrahedron forms a three-parameter group hG_3 (ABCD).

One-parameter subgroups of hG_3 ($ABCD$).—We now proceed to show that the group hG_3 (ABCD) contains ∞^2 one-parameter subgroups. Let us assume among the three parameters, k, k,′ k,″ two

* For the types of collineations in space, see Kan. Univ. Quart., Series A, vol. IX, pp. 58-67.

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relations, viz., $k'=k^{1-r}$ and $k''=k^{1-r+rs}$, and consider only those transformations which satisfy these assumed relations. These two relations are arrived at in the following manner: The cross-ratio along AB is taken to be k, and that along BC to be k^{-r}; hence that along CA is k^{r-1}, or in the direction AC, it is k^{1-r}. The cross-ratio along BC is now k^{-r}; let that along CD be $(k^{-r})^{-s}$ or k^{rs}; then that along DB must be k^{r-rs}, in order that the product of the three cross-ratios taken in the same order round the triangle should be unity. Since the cross-ratio along AB is k, and that along BD is k^{rs-r}, that along DA must equal k^{r-rs+1}; hence that along AD is k^{1-r+rs}, whence $k''=k^{1-r+rs}$. The three cross-ratios around the triangle ACD are, respectively, k^{1-r}, k^{rs}, and k^{r-rs-1}; their product is evidently unity. We now have the following useful table of these cross ratios:

Along AB : k.
" BC : k^{-r}.
" CD : k^{rs}.
" DB : k^{r-rs}.
" AC : k^{1-r}.
" AD : k^{1-r+rs}.

Suppose that k be allowed to vary while r and s remain constant; these restrictions select from the three-parameter group hG_3 (ABCD) a system of ∞^1 transformations which forms a one-parameter subgroup. To show this, take from the group hG_3 (ABCD) two transformations T and T_1, which have the same values of r and s but different values of k. The one-dimensional transformations along the edges of the invariant tetrahedron in the above order and directions are as follows:

$$T : k, k^{-r}, k^{rs}, k^{r-rs}, k^{1-r}, k^{1-r+rs};$$
$$T_1 : k_1, k_1^{-r}, k_1^{rs}, k_1^{r-rs}, k_1^{1-r}, k_1^{1-r+rs}.$$

Their resultant T_2 is given by

$$T_2 : k_2, k_2^{-r}, k_2^{rs}, k_2^{r-rs}, k_2^{1-r}, k_2^{1-r+rs},$$

where $k_2=kk_1$. Thus the resultant T_2 is a transformation having the same values for r and s as T and T_1; thus the group property is established, and the parameter of the group is k. The law of combination of the parameter k in the one-parameter group is expressed by $k_2=kk_1$.

There is a one-parameter group in hG_3 (ABCD) for each real value of r and s, and thus we see that the three-parameter group hG_3 (ABCD) contains ∞^2 one-parameter subgroups. The properties of one of these one-parameter subgroups are readily inferred from the analogous cases of hyperbolic one-parameter groups in one and two dimensions.

THEOREM 2. The three-parameter group hG_3 (ABCD) contains

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∞^2 one-parameter subgroups. For each of these groups r and s have fixed values while k is the variable parameter.

Invariant curves and surfaces of $hG_1\ (ABCD)_{rs}$.—The one-parameter group $hG_1\ (ABCD)_{rs}$ leaves invariant, besides the tetrahedron (ABCD), a system of path curves which are usually curves of double curvature and certain systems of surfaces on which are situated the invariant curves. In order to show this more clearly let us consider the effect on a single point P anywhere in space of all the transformations of the group G_1. Each transformation of the group transforms the point P to some other point P_m. Since the ∞^1 transformations in the group form a continuous system, there are ∞^1 of these points P_m which form a continuous curve, viz., the path curve of the point P.

If we consider in this way the effect of the transformations of the group on all the points of any arbitrary plane, we see that each point of the plane traces a curve. Thus there are ∞^2 of these path curves invariant under all the transformations of G_1. Since our group contains all the pseudo-transformations, corresponding to the values $k=0$ and $k=\infty$, it follows that our path curves all pass through two vertices of the invariant tetrahedron, but not through the other two.

If a surface S be made to pass through ∞^1 of these path curves in such a way that every point on each of these ∞^1 path curves lies on S and also so that every point on S belongs to one of these path curves, then such a surface is an invariant surface of the group G_1. We can best determine these invariant surfaces by resorting to analytic methods.

Equations of invariant surfaces of $hG_1\ (ABCD)_{rs}$.—Let the invariant tetrahedron (ABCD) be the tetrahedron of reference and let T be a transformation of the group G_1 which transforms a point P whose coordinates are (x, y, z, w) to P_1 whose coordinates are x_1, y_1, z_1, w_1. Pass planes through CDP and CDP_1; let these cut AB in Q and Q_1. Then we have the cross-ratio $(ABQQ_1)=k$; hence $\frac{AQ}{BQ} : \frac{AQ_1}{BQ_1}=k$. Using proportional quantities, we have

$$\frac{x_1}{w_1} : \frac{x}{w} = k. \qquad (1)$$

In like manner we have the equations

$$\frac{y_1}{x_1} : \frac{y}{x} = k^{-r}, \qquad (2)$$

$$\frac{z_1}{y_1} : \frac{z}{y} = k^{rs}, \qquad (3)$$

$$\frac{x_1}{z_1} : \frac{x}{z} = k^{r-rs}, \qquad (4)$$

$$\frac{w_1}{y_1} : \frac{w}{y} = k^{r-1}, \qquad (5)$$

$$\frac{w_1}{z_1} : \frac{w}{z} = k^{r-rs-1}. \qquad (6)$$

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Suppose that P_1 is a fixed point and P a movable point depending upon the parameter k. Eliminating k from equations (1) and (3), we get

$$\frac{x^{rs}\, y}{w^{rs}\, z} = \frac{x_1^{rs}\, y_1}{w_1^{rs}\, z_1} = \text{Const.}$$

Clearing of fractions, we have

$$x^{rs}\, y = C w^{rs}\, z. \qquad (I)$$

For different values of C this equation represents a system of invariant surfaces through the path curves of the group.

In like manner eliminating k from equations (2) and (6) we get

$$y^{r-rs-1}\, w^r = C x^{r-rs-1}\, z^r. \qquad (II)$$

Also from (4) and (5) we get

$$x^{r-1}\, y^{r-rs} = C z^{r-1} w^{r-rs}. \qquad (III)$$

It should be noted in each of these cases we have eliminated k from the values of the cross-ratios along opposite edges of the tetrahedron. If we eliminate k from the cross-ratios along edges which lie in a plane face of the tetrahedron, we obtain the equation of the plane path curves which lie in that face. The systems of cones whose vertices are the vertices of the invariant tetrahedron and whose bases are the plane path curves of the opposite faces are also invariant surfaces of the group G_1. Eliminating k from (2) and (3), we have

$$y^{s-1}\, z = C x^s, \qquad (IV)$$

which is the equation of the system of invariant cones whose vertices are at A.

In like manner eliminating k from equations (3) and (6), (1) and (4), (1) and (2), we get

$$z^{r-1}\, y^{1-r+rs} = C w^{rs}, \qquad (V)$$

$$x^{r-rs-1}\, z = C w^{r-rs}, \qquad (VI)$$

$$x^{r-1}\, y = C w^r, \qquad (VII)$$

which are the equations of the invariant cones whose vertices are respectively B, C, and D.

We have thus found seven systems of invariant surfaces of the group G_1; three of these systems are ruled surfaces which pass through four edges of the invariant tetrahedron, and four of them are cones which have their vertices at the vertices of the invariant tetrahedron. The intersections of any two of these systems of surfaces give us the path curves of the group G_1.

THEOREM 3. There are seven distinct families of ruled surfaces invariant under all the transformations of the group $hG_1\,(ABCD)_n$; four of these families are families of cones. The ∞^2 curves of inter-

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section of these invariant surfaces are the invariant path curves of the group G_1.

The geometric meaning of r and s.—It is not difficult to determine the geometric meaning of the two constants r and s. Any tangent to a path curve in the plane ABC cuts the side of the triangle ABC in three points which form with the point of contact a range of four points whose cross-ratio is constant and equal to r. Any tangent to a path curve in space cuts the three planes DAB, DAC, DBC in three points which form with the point of contact a range of constant cross-ratio r. For if path curves and tangent be projected from D on the plane ABC we get the path curves and tangent in the plane ABC with the usual meaning of r.

In like manner s is seen to be the cross-ratio of the point of contact of a tangent to a path curve and the three points where the tangent cuts the three planes ABC, ABD, ACD. In general, a tangent to any path curve in space cuts the faces of the invariant tetrahedron (ABCD) in four points; these with the point of contact of the tangent form a set of five points on a line; r and s are two independent cross-ratios of these five points. All other cross-ratios among these five points may be expressed in terms of r and s. Since these five points are all real, r and s must both be real.

THEOREM 4. The constants r and s are two independent cross-ratios among the range of five points in which a tangent to a path curve cuts the tetrahedron (ABCD) and its point of contact.

§2. TWO-PARAMETER SUBGROUPS OF hG_3 (ABCD).

Having shown that the group hG_3 (ABCD) contains ∞^2 one-parameter subgroups, it will be shown next that these one-parameter subgroups unite in certain instances to form two-parameter subgroups of hG_3 (ABCD). It will be found that a two-parameter subgroup of this kind is characterized by the fact that it leaves invariant one and only one family of surfaces on which lie the path curves of its one-parameter subgroups.

Two-parameter groups leaving invariant a family of cones.—If r remains constant while s assumes in turn all real values, we have a system of ∞^1 one-parameter groups, all of which leave invariant the system of cones given by equation (VII); for the equation of this family of cones is independent of s. The other six systems of surfaces given by equations (I)-(VI) vary as s varies, and are not invariant under all the ∞^2 transformations which leave the cones of (VII) unchanged. This system of ∞^2 transformations leaving a family of cones invariant evidently forms a two-parameter group, the parameters being k and s. There is one such group for every value of r.

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In like manner, if s is constant and r a variable, we get a two-parameter group, leaving invariant the family of cones given by equation (IV). Again, if r and s vary in such a manner that r–rs remains a constant, we get a two-parameter group which leaves invariant the family of cones given by equation (VI). Also, if r and s vary so that $\frac{rs}{1-r}$ is constant, we get another two-parameter group whose invariant family of cones is given by equation (V). We see in this way that the group hG_3 (ABCD) contains four singly infinite systems of two-parameter groups, each of which is characterized by an invariant family of cones.

Two-parameter groups leaving invariant a family of ruled surfaces.—If we let r and s vary simultaneously so that their product, rs, remains a constant, we get thereby a system of ∞^1 one-parameter subgroups of hG_3 (ABCD), all of which leave invariant the family of surfaces given by equation (I). The ∞^2 transformations contained in this system of one-parameter groups, since they have a common invariant, viz., equation (I), form a two-parameter group. There is a two-parameter group for each value of the constant rs.

In like manner we see that if 1–s–1/r is a constant, there results a two-parameter group leaving invariant the family of surfaces given by equation (II). Also if $\frac{r-rs}{r-1}$ remains constant, the resulting system of ∞^2 transformations forms a two-parameter group whose invariant family of surfaces is given by equation (III). Thus we see that the group hG_3 (ABCD) contains three singly infinite systems of two-parameter groups, each of which is characterized by an invariant family of ruled surfaces.

THEOREM 5. The group hG_3 (ABCD) contains four singly infinite systems of two-parameter subgroups, each of which leaves invariant a family of cones; and three singly infinite systems of two-parameter subgroups, each of which leaves invariant a family of ruled surfaces.

§ 3. SOME PROPERTIES OF THE ONE-PARAMETER SUBGROUPS OF hG_3 (ABCD).

Transformations in hG_3 (ABCD) with negative values of k, k', k''.—The group hG_3 (ABCD) contains ∞^3 transformations depending upon three variable parameters k, k', k'', which assume in turn all real values, both positive and negative. Our next problem is to determine whether all the transformations in hG_3 (ABCD) are to be found in these ∞^2 one-parameter subgroups, and what transformations, if any, are common to two or more of these subgroups.

In order to solve these problems we resort to a simple geometrical device where k, k' and k'' are taken to be the rectangular coordinates of

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a point in space. It is evident, since these parameters are independent, that there is a point in space corresponding to every transformation of the group hG_3 (ABCD). All transformations whose parameters satisfy the relations

$$k'=k^{1-r} \text{ and } k''=k^{1-r+rs}$$

form a one-parameter subgroup of hG_3 (ABCD). Hence the curve of intersection of the two cylinders whose equations are $y=x^{1-r}$ and $z=x^{1-r+rs}$ represents a one-parameter group hG_1 $(ABCD)_{rs}$ and the individual points on the curve represent the individual transformations of the group. If we give to r and s all real values we have a system of ∞^2 curves which represents the system of ∞^2 one-parameter subgroups of hG_3 (ABCD).

An examination of the equations $y=x^{1-r}$ and $z=x^{1-r+rs}$ shows that one branch of the curve lies in the first octant for all values of r and s; and if r is an irrational number, the curve lies wholly in the first octant. If r and s are both rational, r with odd numerator and odd denominator, s with even numerator and odd denominator, the curve lies in the first and second octants. If r and s are both rational, r with even numerator and odd denominator, s with odd numerator and even denominator, the curve lies in the first and third octants. If r is rational with odd numerator and even denominator while s is irrational or rational with odd numerator and odd denominator, the curve lies in the first and fourth octants. If r is rational with odd numerator and s rational with odd numerator and even denominator, the curve lies in the first and fifth octants. If r and s are both rational, each with odd numerator and odd denominator, the curve lies in the first and sixth octants. If r and s are both rational, r with even numerator and odd denominator, s with odd denominator, the curve lies in the first and seventh octants. If r and s are both rational, r with odd numerator and even denominator, s with even numerator and odd denominator, the curve lies in the first and eighth octants.

The curves of the family, $y=x^{1-r}$ and $z=x^{1-r+rs}$, contain every point in the first octant, but not every point in the other seven octants. Consequently the group hG_3 (ABCD) contains transformations which are not included in any of its one-parameter subgroups. Such a transformation has one or more of its cross-ratio parameters negative and such that their values do not satisfy algebraic equations of the form $k'^n=k''^m$, $k''^n=k^l$, where l, m and n are integers.

Transformations common to two or more one-parameter subgroups of hG_3 (ABCD).—In order to find all points common to any two curves of the family representing the system of one-parameter subgroups of hG_3 (ABCD), we solve the simultaneous system of equations

$$y=x^{1-r},\ z=x^{1-r+rs};\ y=x^{1-r'},\ z=x^{1-r'+r's'}.$$

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We observe that the points (0, 0, 0), (∞, ∞, ∞), and (1, 1, 1) belong to every curve of the family; hence every one-parameter subgroup of hG_3 (ABCD) contains the identical transformation (1, 1, 1) and the two pseudo-transformations (0, 0, 0) and (∞, ∞, ∞).

From the above equations we have $x^{r'-r}=1$, and $x^{r'-r+rs-r's'}=1$ or $x^{rs-r's'}=1$. Since x is real, it can have only the values ± 1; substituting these values of x in $y=x^{1-r}$ and $z=x^{1-r+rs}$, we see that the real values of y and z are limited to the numbers ± 1. Hence, the only points common to two curves of the family in addition to those mentioned above are (1, 1, -1), (1, -1, 1), (-1, 1, 1), (1, -1, -1), (-1, 1, -1), (-1, -1, 1), (-1, -1, -1). The point (-1, 1, 1) is common to every curve of the family which lies partly in the second octant. The corresponding transformation is an involutoric perspective transformation of type VI, having its vertex at B and the plane ADC for its axial plane. The transformations corresponding to the points (1, 1, -1), (1, -1, 1), (-1, -1, -1) are also involutoric perspective transformations of type VI, with vertices at D, C, and A, respectively, and whose axial planes are the opposite faces of the tetrahedron (ABCD).

The transformations corresponding to the points (1, -1, -1), (-1, 1, -1), and (-1, -1, 1) are involutoric skew perspective transformations of type X, whose skew axes are respectively the edges of AD and CD, AC and BD, AD and BC of the invariant tetrahedron (ABCD). Each of these transformations belongs to every one-parameter subgroup of hG_3 (ABCD) whose representative curve lies partly in the eighth, sixth and third octants, respectively.

THEOREM 6. The ∞^2 one-parameter subgroups of hG_3 (ABCD) do not include all the transformations in hG_3 (ABCD); a transformation not belonging to a one-parameter subgroup has one or more of its cross-ratio parameters negative. Every subgroup hG_1 $(ABCD)_{rs}$ for which r and s are rational contains one involutoric perspective transformation either of type VI or X.

§4. SUBGROUPS OF TYPES VI, VIII AND X IN hG_3 (ABCD).

Subgroups of type VIII in hG_3 (ABCD).—The constants r and s may have such values that all the one-dimensional transformations along the same edge are identical transformations. This may occur in six different ways, since there are six edges of the tetrahedron.

If r=1 while s remains finite, we have an identical transformation along AC. If r=0 while rs remains finite, we have an identical transformation along BC. If $r=\infty$, we see that the transformation along AB is identical. If s=1 and r is finite, we have an identical transformation along BD. If s=0 while r remains finite, the transformation along CD is identical. If rs=r−1, the transformation along AD is identical.

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In the case that a transformation of type I degenerates to type VIII, one of the families of invariant surfaces degenerates into a family of planes intersecting in one edge of the tetrahedron; this edge is opposite the edge which is the line of invariant points. All transformations of type VIII in hG_3 (ABCD) leaving the same edge invariant form a two-parameter group. The path curves of the subgroups of these two-parameter groups are always plane curves.

THEOREM 7. The group hG_3 (ABCD) contains six two-parameter subgroups of type VIII; these are given when $r=1, 0, \infty$; and $s=1, 0, \frac{r-1}{r}$.

Subgroups of type VI in hG_3 (ABCD).—For certain values of r and s a transformation of type I reduces to type VI. In such a case all points in one of the invariant planes of type I are invariant points, and all lines through the opposite vertex of (ABCD) are invariant lines.

Let $r=0$ and let s have any finite value; then the transformations along BC, CD and DB are all identical; hence the two-dimensional transformation in the face BCD is identical. At the same time the cross-ratios along AB, AC and AD are all equal to k. Such a transformation is evidently of type VI. Let $r=1$ and $s=0$; then the two-dimensional transformation in the face ACD is identical, and the one-dimensional transformations along BA, BC and BD are all equal. Again, let $r=\infty$ and $s=1$; then the two-dimensional transformation in the face ABD is identical, and the one-dimensional transformations along CA, CB and CD are all equal. Finally, let $r=\infty$ and $s=\infty$; then every point in the face ABC is an invariant point and the one-dimensional transformations along DA, DB and DC are all equal.

It is evident in each of the above cases that the invariant surfaces are all planes or cones and the path curves are all straight lines.

THEOREM 8. The group hG_3 (ABCD) contains four one-parameter subgroups of type VI; these are given by the following sets of values of r and s: $(0, s), (1, 0), (\infty, 1), (\infty, \infty)$.

Subgroups of type X in hG_3 (ABCD).—For certain values of r and s a transformation of type I reduces to one of type X. From the nature of type X it is evident that it must occur as a special case of type VIII, when the two one-dimensional transformations along opposite edges of (ABCD) are identical transformations.

Let $r=1$ and $s=1$; then the one-dimensional transformations along AC and BD are both identical transformations, and thus every point on each of these edges is an invariant point. The cross-ratios along AB, AD, CB and CD are all equal. The invariant families of surfaces I–VII reduce for $r=1$ and $s=1$ to the following:

$$xy=Czw,\ xw=Cyz,\ x=Cz,\ \text{and}\ y=Cw.$$

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The path curves are evidently straight lines and constitute the congruence of lines joining every point on AC to every point on BD.

Again, let $r=\infty$ and $s=0$ with the condition that $rs=0$; then the transformations along AB and CD are both identical, while those along AC, AD, BC and BD are all equal. The invariant surfaces and path curves are analogous to those above. In like manner, if we make $r=0$ and $s=\infty$, and $rs=-1$, we get identical transformations along BC and AD; the cross-ratios along AB, AC, DB and DC are all equal, the invariant surfaces are pencils of quadrics and pencils of planes, the path curves are all straight lines.

THEOREM 9. The group $hG_8(ABCD)$ contains three one-parameter groups of type X; these are given by the following sets of values of r and s: $(1, 1)$, $(\infty, 0)$, $(0, \infty, rs=-1.)$

§5. SOME SPECIAL SUBGROUPS OF $hG_8(ABCD)$.

Subgroups with invariant quadric cones.—For certain values of r and s the invariant cones whose equations are (IV)-(VII) are cones of the second order. One of these families of cones will be of the second order when the plane path curves in one the faces of the tetrahedron are conics.

Equation (IV) represents a family of quadric cones for three values of s, viz., $s=-1, 2, \frac{1}{2}$; equation (V) represents quadric cones when $\frac{rs}{r-1}=-1, 2, \frac{1}{2}$; equation (VI) represents quadric cones when $r-rs=-1, 2, \frac{1}{2}$; equation (VII) represents quadric cones when $r=-1, 2, \frac{1}{2}$. Consider the case when $r=-1$; s may assume ∞^1 different values, and hence there are ∞^2 one-parameter groups which leave invariant the same family of quadric cones. These form a two-parameter group. The vertex of the cones of the family are at D, and the lines DA and DB are elements common to all the cones of the family. Thus we see that there are twelve two-parameter subgroups of hG_8 (ABCD) which leave invariant a family of quadric cones.

THEOREM 10. The group hG_8 (ABCD) contains twelve two-parameter subgroups each of which leaves invariant a family of quadric cones; these are given by the values of r and s as follows: $r=-1, 2, \frac{1}{2}$; $s=-1, 2, \frac{1}{2}$; $r-rs=-1, 2, \frac{1}{2}$; $\frac{rs}{r-1}=-1, 2, \frac{1}{2}$.

Subgroups with invariant quadric surfaces.—We now seek the most general conditions under which the invariant surfaces of a one-parameter subgroup of hG_8 (ABCD) shall be a family of quadric surfaces. One or more of the three families of surfaces whose equations are (I), (II), (III) will reduce to quadrics for certain values of r and s. The surfaces given by (I) are quadrics when $rs=\pm 1$; equation (II) gives quadrics when $r-rs-1=\pm r$; equation (III) yields quad-

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rics when $r-1=\pm(r-rs)$. The condition $r-rs-1=\pm r$ reduces to $rs=-1$ and $rs=2r-1$; the condition $r-1=\pm(r-rs)$ reduces to $rs=1$ and $rs=2r-1$. Hence we have only three relations beween r and s for which at least one family of invariant surfaces are quadrics.

Putting $rs=1$ in (I), (II), (III), we get, after reduction,

$$(I),\ xy=Czw;\ (II),\ y^{r-2}w=Cx^{r-2}z;\ (III),\ xy=Czw.$$

Thus the first and third families of surfaces reduce to the same family of quadrics.

Putting $rs=-1$ in (I), (II), (III), we have

$$(I),\ xz=Cyz;\ (II),\ xz=Cyw;\ (III),\ x^{r-1}y^{r+1}=Cz^{r-1}w^{r+1}.$$

Here we see that (I) and (II) give the same system of quadrics. Putting $rs=2r-1$ in (I), (II), (III), we get

$$(I),\ x^{2r-1}y=Czw^{2r-1};\ (II),\ xw=Cyz;\ (III),\ xw=Cyz.$$

From these three cases we see that, if one of our families of invariant surfaces are quadrics, another is also, and these two families of quadrics coincide.

The invariant tetrahedron (ABCD) is the common self-polar tetrahedron of these families of quadrics. All quadrics of the system $xy=Czw$ pass through the edges AC, CD, AB, and BD; the edges AD and BC are reciprocal polars of all quadrics of the family. Similar properties hold for the other two families $xz=Cyw$ and $xw=Cyz$.

Each of these systems of quadrics remains invariant under ∞^2 transformations which form a two-parameter subgroup of hG_3 (ABCD).

THEOREM 11. There are three two-parameter subgroups of hG_3 (ABCD) each of which leaves invariant a family of quadric surfaces; these are given by $rs=1$, $rs=-1$, $rs=2r-1$.

Subgroups whose path curves are all conics.—We now proceed to investigate the one-parameter subgroups of hG_3 (ABCD) whose path curves are all conics. Since conics are plane curves, such a one-parameter group must be of type VIII. We find in §4 that there are six two-parameter subgroups of type VIII in hG_3 (ABCD); hence, a one-parameter subgroup of hG_3 (ABCD) whose path curves are all conics must be a one-parameter subgroup of one of these groups of type VIII.

To obtain one of these two-parameter subgroups of type VIII let $s=1$. The line DB is a line of invariant points, and all planes through the opposite edge AC are invariant planes. The path curves are all alike in these invariant planes, and hence it is sufficient to examine them in one of these planes, as ABC. The path curves in the plane ABC are conics for three different values of r, viz., $r=-1, 2, \frac{1}{2}$.

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For $r=-1$, 2, and $\frac{1}{2}$ the conics have double contact at A and C, B and C, and A and B, respectively.

The case where $r=-1$ is essentially different from the other two cases where $r=2$ and $r=\frac{1}{2}$. In the first case the conics in all the planes through AC have double contact at A and C; in the second case the conics in all these planes have only one point in common, C when $r=2$ and A when $r=\frac{1}{2}$. The invariant surfaces in the two cases are very different and worthy of attention. Let $s=1$ and $r=-1$ in equations (I), (II), (III); we thus get

$$(I),\ xz=Cyw;\ (II),\ xz=Cyw;\ (III),\ x=Cz.$$

In this case we have a family of invariant quadrics. Again, let $s=1$ and $r=2$ in the same equations, and we have

$$(I),\ x^2y=Cw^2z;\ (II),\ xw^2=Cyz^2;\ (III),\ x=Cz.$$

Let $s=1$ and $r=\frac{1}{2}$, and we get

$$(I),\ xy^2=Cwz^2;\ (II),\ x^2w=Cy^2z;\ (III),\ x=Cz.$$

In both these latter cases the invariant surfaces are ruled surfaces of the third order.

Instead of taking the edge BD for the line of invariant points any other one of the six edges may be made the line of invariant points; hence there are six such cases as the above to be considered.

THEOREM 12. There are eighteen one-parameter subgroups of hG_8 (ABCD) for which the path curves are conics; six of these groups leave invariant a family of quadrics and twelve of them leave invariant families of cubic surfaces. The first six are given by the following values of r and s: $(-1, 1)$, $(1/2, 0)$, $(2, 1/2)$, $(1, -1)$, $(0, \infty, rs=-1)$, $(\infty, 2)$. The remaining twelve result from the following values of r and s: $(2, 1)$, $(1/2, 1)$, $(2, 0)$, $(-1, 2)$, $(1/2, -1)$, $(1, 2)$, $(1, 1/2)$, $(0, \infty, rs=2)$, $(0, \infty, rs=1/2)$, $(\infty, -1)$, $(\infty, 1/2)$, $(-1, 2)$.

Subgroups whose path curves are twisted cubics.—If we give to r and s such values that two of the families of invariant cones (IV) . . . (VII) are quadric cones so situated that all the cones of both families have one edge of the tetrahedron (ABCD) in common, the path curves of the resulting one-parameter groups will be twisted cubics; for the intersection of two quadric cones having one element in common is a twisted cubic passing through the vertices of the two cones and having the common element for a secant line.

For example, let $r=-1$ and $s=-1$; equations (IV) and (VII) reduce respectively to

$$xz=Cy^2 \text{ and } yw=Cx^2.$$

The first equation represents a family of quadric cones having double contact along AB and AD; the second represents a family of cones

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having double contact along DC and DA. Since every cone of each family has the line AD in common, their curves of intersection are a system of ∞^2 twisted cubics passing through A and D. For these values of r and s the invariant systems of surfaces given by (1), (II), (III) become

$$(I),\ xy=Czw;\ (II),\ x^3z=Cy^3w;\ (III),\ xy=Czw.$$

Thus we see that the cubic path curves also appear as the intersection of a family of quadrics with a family of quartics.

Again, let us put $r=1/2$ and $s=2$; equations (IV) and (VII) reduce respectively to

$$yz=Cx^2 \text{ and } xw=Cy^2.$$

These two families of quadric cones have also the element AD in common. Equations (I), (II), (III) become for these values of r and s

$$(I),\ xy=Czw;\ (II),\ x^3w=Cy^3z;\ (III),\ xy=Czw.$$

The path curves are again twisted cubics through A and D and lie on the family of quadrics $xy=Czw$; but they now appear as the intersection of this family of quadrics with another family of quartics.

In like manner it can be shown that the path curves are twisted cubics for ten other pairs of values of r and s, as follows: $r=3, s=1/3$; $r=3/2, s=1/3$; common chord BC: $r=-2, s=1/2$; $r=-1/2, s=2$; common chord AC: $r=2, s=3/2$; $r=-1, s=3$; common chord CD: $r=2, s=-1/2$; $r=1/2, s=-2$; common chord BD: $r=1/3, s=-1$; $r=2/3, s=1/2$; common chord AB.

THEOREM 13.—There are twelve one-parameter subgroups of hG_8 (ABCD) for which the path curves are twisted cubics; these are given by the following values of r and s: $(r=-1, s=-1)$, $(r=1/2, s=2)$, $(r=3, s=1/3)$, $(r=3/2, s=1/3)$, $(r=-2, s=1/2)$, $(r=-1/2, s=2)$, $(r=2, s=3/2)$, $(r=-1, s=3)$, $(r=2, s=-1/2)$, $(r=1/2, s=-2)$, $(r=1/3, s=-1)$, $(r=2/3, s=1/2)$.

§ 6. THE GROUPS eG_8 (ABCD) AND eeG_8 (ABCD) AND THEIR SUBGROUPS.

We shall now consider briefly the two cases where the invariant tetrahedron (ABCD) is not real in all of its parts. The first, called the single elliptic case, is where the tetrahedron has two real and two conjugate imaginary vertices; the second, called the double elliptic case, is where the tetrahedron has two pairs of conjugate imaginary vertices. These three-parameter groups are designated by eG_8 (ABCD) and eeG_8 (ABCD), respectively.

The group eG_8 (ABCD) and its subgroups.—Let B and C be a pair of conjugate imaginary vertices of the tetrahedron (ABCD). The cross-ratios k and k′ along the conjugate imaginary lines AB and

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AC are conjugate imaginary quantities; also those along DC and DB are conjugate imaginary quantities. The cross-ratio k″ along AD is real, and that along BC is of the form exp. ni θ. As in the hyperbolic case, we may put $k' = k^{1-r}$ and $k'' = k^{1-r+rs}$; r and s are usually both complex quantities. It can be shown without difficulty that the condition that the collineation shall be real requires that r shall be of the form $1 + \text{exp. } 2i\,\phi$, and s of the form $\frac{\text{exp. } 2i\psi}{\text{exp. } 2i\psi + 1}$. In the complex plane the locus of r is the unit circle about the unit point, and the locus of s is the line $x = 1/2$.

The cross-ratios along the six edges of the tetrahedron may be written:

$$\begin{aligned}
AB &: \text{exp. } (\tan\phi + i)\,\theta,\\
BC &: \text{exp. } -2i\,\theta,\\
CD &: \text{exp. } (\tan\psi + i)\,\theta,\\
DB &: \text{exp. } (-\tan\psi + i)\,\theta,\\
AC &: \text{exp. } (\tan\phi + i)\,\theta,\\
AD &: \text{exp. } (\tan\phi + \tan\psi)\,\theta.
\end{aligned}$$

In these expressions θ is the variable and assumes in turn all real values from $-\infty$ to $+\infty$. Since k is real, both positive and negative, while the value of exp. $(\tan\phi + \tan\psi)\,\theta$ is only positive, it follows that half of the transformations in eG_3 (ABCD) are not contained in its one- and two-parameter subgroups, viz., those for which k is negative.

The group eG_3 (ABCD) contains two real subgroups of type VI, the vertices being A and D; it also contains two real subgroups of type VIII, one hyberbolic and the other elliptic, whose axes of invariant points are, respectively, BC and AD; it also contains one subgroup of type X, which is common to the two subgroups of type VIII.

The group eG_3 (ABCD) has only two real two-parameter subgroups leaving invariant a family of quadric cones. These two families of cones do not have an element in common; hence there are no real subgroups leaving invariant a family of cubic path curves. When ϕ and ψ are supplementary, one of the families of invariant surfaces consist of quadrics. These statements may be easily verified by the reader.

The group eeG_3 (ABCD).—Let AD and BC be taken as the two real edges of the invariant tetrahedron (ABCD) in the double elliptic case. Along these real edges the one-dimensional transformations are elliptic, so that the cross-ratios are both of the form exp. ni θ. It follows from these conditions that k must be assumed in the form of

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exp. i θ, and that r and s are both real. The cross-ratios along the six edges of the tetrahedron (ABCD) are written thus:

$$AB : k = \text{exp. } i\,\theta,$$

$$BC : k^{-r} = \text{exp. } ri\,\theta,$$

$$CD : k^{rs} = \text{exp. } rsi\,\theta,$$

$$DB : k^{r-rs} = \text{exp.}(r - rs)i\,\theta,$$

$$AC : k^{1-r} = \text{exp.}(1 - r)i\,\theta,$$

$$AD : k^{1-s+rs} = \text{exp.}(1 - r + rs)i\,\theta.$$

It is now evident that every transformation in eeG_3 (ABCD) is to be found in some one of its one-parameter subgroups. The group eeG_3 (ABCD) contains two real subgroups of type VIII, both elliptic, and one of type X, which is common to the two of type VIII.

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THE DIMORPHISM OF CAMBARUS, I.

BY J. ARTHUR HARRIS.

THE existence of two markedly different forms of males in the genus *Cambarus* has long been known. The fact was first noticed by Louis Agassiz and Henry James Clark,[1] and communicated[2] by the former to Dr. Hermann A. Hagen, who verified the observation for all the species of *Cambarus*, of which he had opportunity of examining a large number of specimens.[3] Doctor Hagen, in his monograph, whenever material was available, described both forms of males, designating them as form I and form II. Since that time, in taxonomic work, a complete description has always covered both forms of the male; a fact of no small importance, since the discrepancies in the descriptions of some of the earlier writers may be due to the fact that the presence of two forms of males in each species had not yet been recognized.

The external differences between the first- and second-form males have been well described by Hagen[4] and Faxon.[5]

The differences may here be just as well stated in Doctor Faxon's words:[6]

"The differences between the two forms affect more especially the first pair of abdominal appendages, organs concerned in the act of coition, but also extend to the general form and sculpture of the body. In one form [unhappily called by Doctor Hagen the 'second-form'] the first pair of abdominal appendages have a structure nearly like that seen in all young males. The hook on the third joint of the third [in some species, of the third and fourth] pair of legs is small, and in the sculpture of the shell and shape of the claws this form approaches the female. In the other form [Hagen's 'first-form'], the articulations near the base of the first pair of abdominal appendages are gone and the whole member is much more highly specialized, the terminal hooks being horny, more widely separated, and in every way more highly developed; in those species with bifid tips to these appendages, the branches are longer, slender, more widely separated, and stiffer; the hooks on the thoracic legs are longer and more perfectly finished, the sculpture of the whole body is more pronounced, and the claws are longer and more powerful. No intermediate conditions are found, and there is no relation between these forms and the size of the individual, the 'second form' being large and the 'first form' small, or *vice versa*."

1. See Faxon (Walter), "On the so-called Dimorphism in the Genus *Cambarus*," Amer. Jour. Sci., vol. XXVII, pp. 42-44.

2. See Hagen (Hermann A.), "Monograph of the North American Astacidæ," Ill. Cat. Mus. Comp. Zool., Harvard Coll. 1870.

3. Hagen, loc. cit., p. 24.

4. Hagen, loc. cit.

5. Faxon, loc. cit. Also, "A Revision of the Astacidæ," pt. I, Mem. Mus. Comp. Zool., vol. X, No. 4. 1885.

6. Faxon, "On so-called Dimorphism," etc.

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Doctor Hagen made an anatomical examination[7] of first- and second form males of *C. acutus* Girard, *C. virilis* Hagen, and *C. bartonii* Fabricius. His observations were made from a very limited number of specimens—probably only two from each species—and no note was made of the time of year the material was taken, a factor the significance of which he seems to have entirely overlooked. His observations were that the testis was decidedly larger in the first- than in the second-form. He says, in fact: "The sexual parts of the second-form males are so much less developed that it would be allowable to consider them as sterile." Hagen's idea was that in the older males of the second-form the sexual organs have failed to develop and are consequently non-functional. He says: "But the great number of full-grown second-form specimens in every species, which are often even larger than the first-form males, seems to prove that they are individuals which have remained in a sexual stage that does not agree with their corporal development—in short, they are, perhaps, sterile."

The size of the arthropod testis, in fact, depends largely upon the condition of the elements, being, for instance, larger when the sperm-cells are in the spermatocyte stages than when the spermatozoa are mature, and being, of course, smaller still after the testis has been evacuated.

So far as I have been able to observe, the testis of first- and second-form males of the same size, taken at the same season of the year, are equally developed, it being impossible to determine from an examination of the testis alone whether a given individual is first- or second-form.

Faxon[8] observed that the so-called first- and second-form males merely represent alternating stages in the life of the individual. Specimens of *C. rusticus* Girard kept in his laboratory copulated freely. Shortly after they exuviated, and, while yet soft, they were thrown with their casts into alcohol. Upon later examination, it was observed that the casts were first-form—the form in which the animal had approached the female—while the animals themselves were second-form.

The same was noticed for a specimen of *C. propinquus* Girard which had been preserved with its cast.

I have had the opportunity of watching quite closely a small stagnant pond near Lawrence, Kan., in which occur *C. gracilis* Bundy, *C. virilis* Hagen, and *C. immunis* Hagen. As *C. immunis* was by far the most abundant, observations were made on it. In the late summer and autumn, the proportion of first-form males gradually increased; there seems to be, so far as my observations go, no definite

7. Hagen, loc. cit., pp. 22-24.
8. Faxon, "On so-called Dimorphism," etc.

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time at which exuviation takes place. This point, however, should be determined more definitely. In the spring of 1901, *C. immunis* appeared in the above-mentioned pond early in March. All males collected up to April 15 were first-form. On April 20, the pond was again examined and a large number of second-form males, yet soft from exuviation, were found. On April 25, the most of the males taken were second-form, and none of them had yet attained the normal degree of hardness. A large proportion of the first-form males were evidently nearly ready to exuviate. None, however, were observed in the act. Upon slipping the old "shell" from first-form males ready to exuviate, the animals in their new condition were plainly seen to be second-form. Thus, my somewhat more extended observations for *C. immunis* Hagen confirm Doctor Faxon's important discovery, that the "first" and "second" forms are simply alternating periods in the life of the individual.

While neither so extended nor careful as for *C. immunis*, my observations on the habits of *C. virilis* led me to believe that the process is the same in this species.

Two individuals taken in the above-mentioned pond are deserving of special consideration. The first (No. 34), a specimen of nearly three inches in length, was collected on the morning of April 29, 1901, and thrown with many others into a collecting can. In the afternoon, when the material was removed and examined, it was noticed that this specimen had died during the process of exuviation. The cast was plainly second-form, as was also the animal in its new condition. The pleopods and the hooks on the ischiopodites were decidedly and plainly second-form in both the cast and the exuviated animal. The old chelæ resembled those of the second-form, but those of the soft animal were so much distorted that they offered no evidence of value.

The other specimen (No. 35) was collected while very soft from exuviation. It was in every respect a clearly marked first-form male, and, while the cast was not secured, it seems altogether probable that this animal must have passed the winter in the first-form condition. All males taken up to this time in the spring, with the one exception of No. 34, were first-form males, as were all males of this species taken late in the fall.

C. immunis ceases to be constantly second-form long before it attains the size of No. 34. No. 35, while a large specimen for *C. immunis*, was very slightly, if any, larger than other specimens collected in the same place, which changed from first- to second-form upon exuviation. This would seem to indicate that, if there is finally reached a period in the life of the animal in which it is constantly in the first-

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form condition and if No. 35 had reached this stage, the beginning of this period varies with different individuals.

Thus, in the two cases mentioned above, it would seem that we have exceptions to the general rule of alternation of forms; having in one case a large second-form individual retaining the second-form condition after exuviation, and in the other an animal which was probably in the first-form condition remaining first-form after exuviation. It seems to me not at all improbable that No. 11 also represents one of these "abnormal" changes, being large enough to be in first-form condition, and yet again assuming the second-form just at the time when all others are first-form.

As to the microscopic condition of the testes, these specimens are not very dissimilar to others collected the same spring (Nos. 21 to 37). Of No. 34, all the lobes and the vas deferens were sectioned. The lobe is made up proximally of emptied follicles. Upon this follows an extensive zone of spermatocytes, many of them in active mitosis. The distal end of the lobe is occupied by the spermatogonial zone, which is composed of only a few follicles in one of the lobes. The vas deferens is filled with spermatozoa. Of No. 35, two lobes and the vas deferens were sectioned. In this specimen the posterior lobe is very much larger than either of the anterior lobes, but, so far as our present consideration is concerned, this seems to me to be of no great significance. The condition of the elements is very similar to that of No. 34. The vas deferens is well filled with spermatozoa. In both of these specimens we notice a predominance of spermatocytes. The relative extent of the spermatocytes as compared with the other zones is, with the exception of the one lobe of No. 34 mentioned above, not so great as in the one lobe of No. 37 which was examined. With the exception of the proportionately greater extent of the spermatocyte zone, No. 37 is very similar to Nos. 34 and 35.

Faxon, in his paper on "Dimorphism," says: "I will add that the males of extraordinary size which I have seen are all of the 'first-form.' Do these very old individuals cease to molt? Do they become permanently capable of reproduction?" My observations, so far as they extend, confirm those of Doctor Faxon. Having seen some very large second-form males of both *C. virilis* and *C. immunis*, I must add, however, that this observation is true of only the extraordinarily large individuals. While such a hypothesis seems not at all unreasonable, I should like to examine a much larger series of material than I have yet had the opportunity of doing before I say that the males reach a permanently first-form condition. It seems to me improbable that the old individuals should cease to molt, but not at all improbable that they should continue in the same form after molting.

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Doctor Faxon suggests[9] that Doctor Hagen's method of designating the two phases is not so happy as might be desired.

It would, perhaps, be better if the terms were just reversed, and the male in the condition to approach the female were called form II, since that designated by Hagen as form II is the form in which we first find the animal. While it is not at all descriptive, I can see, other than that mentioned above, no serious objection to Hagen's terminology, especially since it is so well established in the literature. It surely is very convenient, while I am not at all sure that a descriptive term which would not be cumbersome could be easily found.

No dimorphism in the males has been observed in *Astacus*, nor, so far as I have been able to learn, has any indication of it been found in any other genus of the Astacidæ, unless it be in the subgenus *Cambaroids*, where Faxon[10] suspects the presence of two forms of the male, as in *Cambarus*. Should this be found to be true, it would certainly be of great interest from a phylogenetic point of view. It must be borne in mind, however, that the Parastacine genera have not been nearly so thoroughly studied as those of the Potamobine.

A fact which I believe has not heretofore been considered in the literature on the dimorphism of *Cambarus* nevertheless seems to me significant. In *Astacus*, according to Chantran,[11] after the third year the males molt twice, first in June and July, afterwards in August and September, and the females once, from August to September, annually. According to Huxley,[12] copulation takes place immediately after *the completion of ecdysis*, in the early autumn. It is to be observed that if the alternation of forms in *Cambarus* noticed by Faxon occurs regularly year after year, which my observations tend to prove for both *C. immunis* and *C. virilis*, the parallel between the two is quite striking; the spring ecdysis of *Astacus* corresponding to that which brings *Cambarus* into the second-form after copulation, while the autumn ecdysis of *Astacus* corresponds to that which brings *Cambarus* back into the form in which it is ready to approach the female.

Neither Hagen's nor Faxon's material was in condition, having lain so long in alcohol, for a microscopic determination of the condition of the contents of the testis. My object in this study has been to supply observations on this point, hoping, by careful comparison

9. Faxon, "On so-called Dimorphism," etc.

10. Faxon, Monograph, p. 227.

11. Chantran, S. (1) "Observations sur la formation des pierres chez les écrevisses," Compt. Rend., t. 78, pp. 665–667. (2) "Sur le mechanisme de la dissolution intra-stomacale des concrétions gastriques des écrevisses," Compt. Rend., t. 79, pp. 1230, 1231. (3, 4) "Observations sur l' histoire naturelle Ecræsses," Compt. Rend., t. 69 and 73.

I have not seen these papers, but make the statement on the authority of Dr. C. L. Herrick, "The American Lobster," Bull. U. S. Fish Com., vol. XV (Washington, 1896), and Huxley (T. H.), "The Crayfish." —J. A. H.

12. Huxley, loc. cit.

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of the sexual organs, to get some idea of the relation of the reproductive elements to the physical condition of the animal, and in this way come a little nearer to the determination of the true significance of the occurrence of the two forms.

As the title indicates, I do not intend this as a final paper, there being many important points yet to be ascertained before this interesting problem is fully solved. I feel, however, that, in addition to the general survey of the subject, the question, the answer to which was the original subject of the investigation, has been definitely and conclusively answered, and that the results obtained are of sufficient interest to warrant their appearance here, even before other points which have been suggested in the course of the work are decided.

My material was fixed in Flemming's fluid, sometimes with a varying amount of acetic acid, in hope of counteracting the tendency to a vacuolation of the cytoplasm during the process of division, embedded in paraffin, and sections prepared by the usual cytological methods. Heidenhein's iron-hæmatoxylin and the safranin-gentian-violet-orange-G methods were used principally as staining reagents.

I wish to express here my gratitude to Prof. C. E. McClung and Mr. W. S. Sutton, of the department of zoology, University of Kansas, where the work was done, for useful suggestions.

It will be observed that in comparing the condition of the testes of different individuals, I have frequently used some qualifying term; as, for example, "Condition about the same as No. ——." This course seemed necessary to strict accuracy; for while, so far as the essential parts are concerned, they may be alike, it must be borne in mind that considerable individual variation is to be expected. Various causes affect the relative development of the germ-cells in different individuals. In *Cambarus*, the greatest variation occurs in the general form of the testis—a condition which would imply considerable variation in the relative shape and arrangement of the different germ-cell zones. The normal testis is three-lobed—two anterior and one posterior; yet those which have become almost completely four-lobed through the division of one of those already existing are not at all uncommon.

The following table shows the condition of the testes of a number of individuals of the two forms. Usually but one lobe was examined; however, in cases where more than one lobe was sectioned, the condition was usually found to be essentially the same. It will be noted that some of the material is not in the best condition, having been prepared under unfavorable circumstances. I might say, however, that in no case have conclusions been even suggested from poor sections which seemed in any important way different from other preparations with which they were compared. The greater part of my

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material is, I believe, in as good condition as that upon which many of our cytological papers are based.

No. 1. *C. immunis.* F. I. About two inches long. August 24, 1900.

One lobe sectioned. At the proximal end are a few emptied follicles and more with mature spermatozoa. Also various stages of spermatid transformation, the earlier stages being for the most part towards the distal end. The spermatids extend somewhat more than one-half the length of the lobe. Then follow spermatocytes; and finally an area of spermatogonia, about one-sixth the length of the lobe in width. An occasional division figure is seen among these spermatogonia.

No. 2. *C. immunis.* F. I. About two inches long. July 27, 1900.

Sections not in plane to show regions to best advantage, but condition seems to be about same as No. 1.

No. 3. *C. immunis.* F. II. About two and one-half inches long. August 2, 1900.

All lobes sectioned. Sections of anterior lobes not perfect. One of anterior lobes seems to have an unusually large number of spermatogonia. Condition otherwise seems to be about same as No. 1.

No. 4. *C. immunis.* F. II. Size of individual not recorded; probably about two inches long. Still slightly soft from exuviation.

Only one lobe sectioned. With the exception of a little different appearance of the spermatogonia, which, from comparison with other material, seems to me to be unimportant in this connection, this seems to agree exactly with No. 1.

No. 5. *C. immunis.* F. I. About two inches long. August 24, 1900.

One lobe sectioned. Proximal end shows follicles with mature spermatozoa. Farther back are seen follicles containing various stages of spermatid transformation; then follow spermatocytes and finally spermatogonia. Condition practically same as No. 1. Vas deferens contains a considerable number of spermatozoa.

No. 6. *C. immunis.* F. I. About two inches long. August 24, 1900.

Only one lobe sectioned. In about same condition as No. 1.

No. 7. *C. immunis.* F. I. About two and one-half inches long. August 31, 1900.

One lobe sectioned. Conditions about the same as No. 1. A section through the vas deferens shows the presence of a considerable number of spermatozoa.

No. 8. *C. immunis.* F. II. About three to three and one-half inches long. August 24, 1900.

One lobe sectioned. Condition practically identical with No. 1.

No. 9. *C. immunis.* F. II. About two and one-half inches long. August 31, 1900.

One lobe sectioned. Condition almost exactly same as that of No. 1.

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No. 10. *C. immunis.* F. II. About two and one-half inches long. August 31, 1900.

One lobe sectioned. Condition about same as No. 1.

No. 11. *C. virilis.* F. II. Perfectly soft from shedding. A little over two inches long. September 4, 1900.

One lobe sectioned. Seems to be abnormal. There are present, however, almost mature elements, spermatids, spermatocytes, and spermatogonia.

No. 12. *C. immunis.* F. II. About two inches long. August 24, 1900.

One lobe and vas deferens sectioned. Condition of lobe practically same as No. 1. Vas deferens contains many spermatozoa.

No. 13. *C. immunis.* F. I. Good-sized individual. Probably two and one-half or three inches long. Collected in burrow, October 13, 1900.

One lobe and vas deferens sectioned. Proximal part of lobe made up of emptied follicles and those yet filled with mature spermatozoa. Farther back are seen spermatids in various stages of transformation, some of them quite early. A few follicles with spermatocytes are noted. Bordering immediately on the spermatid region, or upon the scattered follicles of spermatocytes, is seen the distal region of spermatogonia, in which a division figure is occasionally to be noted.

No. 14. *C. immunis.* F. I. About two and one-half inches long. August 21, 1900.

Material so badly oriented and broken up in preparation that an *exact* determination of the different regions is impossible. Spermatozoa, spermatids, spermatocytes and spermatogonia are found. Apparently, it is practically the same condition as No. 1. Vas deferens shows considerable number of spermatozoa.

No. 16. *C. immunis.* F. I. About two or two and one-half inches long. August 21, 1900.

One lobe examined. Condition about same as No. 1.

No. 17. *C. immunis.* F. II. About two inches long. August 24, 1900.

One lobe sectioned. Condition practically same as No. 1.

No. 18. *C. immunis.* F. II. About two and one-half inches long. August 2, 1900. Still fairly soft from shedding.

Condition practically same as in No. 1.

No. 20. *C. virilis.* F. I. About two and one-half inches long. Collected in ice-cold water in creek, January 18, 1901.

Sections not longitudinal, and so arrangement of regions is uncertain. Most of the follicles are filled with mature spermatozoa; in some few the spermatozoa are apparently not quite mature, not being massed together at the center. Follicles containing spermatocytes, and a greater number containing spermatogonia, also occur. The vas deferens contains a good many spermatozoa, but is not nearly full.

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No. 21. *C. immunis.* F. I. About two or two and one-half inches long. March 19, 1901.

All lobes of testis sectioned. Proximal ends made up of emptied follicles. Beyond these are some still containing apparently the original number of spermatozoa of the preceding season. A few follicles are filled with large primary spermatogonia. An occasional follicle contains spermatocytes in fine spireme condition. Those of the distal end contain spermatogonia, among which an occasional division figure is to be seen. The vas deferens is well filled with spermatozoa.

No. 22. *C. immunis,* F. I. Two and one-third or three inches long. March 19, 1901.

Two lobes and vas deferens sectioned. Is in practically same condition as No. 21.

No. 23. *C. immunis.* F. I. About two and one-half inches long. March 22, 1900.

Two anterior lobes and vas deferens sectioned. Condition practically same as in No. 21.

No. 24. *C. immunis.* F. I. About three inches long. March 22, 1901.

Vas deferens examined. Well filled with spermatozoa.

No. 25. *C. immunis.* F. I. About two and one-half inches long. March 24, 1901.

Somewhat broken up in preparation. Condition about same as No. 21. Spermatocytes not common. Follicles do not contain so many spermatozoa.

No. 26. *C. immunis.* F. I. About two and one-fourth inches long. March 27, 1901.

Two lobes sectioned. Condition largely same as No. 21. No spermatocytes were noticed and no follicles still containing any considerable number of spermatozoa. Spermatogonial region more extensive than in No. 21.

No. 27. *C. immunis.* F. I. Early May, 1900.

Sections rather poor. Lobe seems to be made up of the proximal area of emptied follicles and a large distal area of spermatogonia, among which occasional division figures are to be observed. The vas deferens is well filled with spermatozoa.

No. 28. *C. immunis.* F. II. April, 1900.

Sections poor. Conditions practically same as in No. 27. Vas deferens well filled with spermatozoa.

No. 29. *C. virilis.* F. II. May 5, 1900.

Sections poor. Conditions probably much the same as in Nos. 27 and 28.

No. 30. *C. virilis.* F. II. May 5, 1900.

Condition largely same as the three preceding. In Nos. 27 to 30, taken in the spring of 1900, we find essentially the same conditions, both in *C. immunis* and *C. virilis*, as those observed in No. 21.

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No. 31. *C. immunis.* F. II. About three inches long. Slightly soft from exuviation. April 20, 1900

Two lobes sectioned. Condition same as No. 26.

No. 32. *C. immunis.* F. II. About two and one-half inches long. Very soft from exuviation. April 21, 1901.

One lobe sectioned. Condition seems to be about the same as No. 36. Vas deferens well filled with spermatozoa.

No. 33. *C. immunis.* F. I. About two and one-half inches long. Did not seem to be nearly ready to exuviate. April 21, 1901.

One lobe sectioned. Condition much the same as in No. 31. Vas deferens well filled with spermatozoa.

No. 34. See body of paper, pages 50 and 51.

No. 35. See body of paper, pages 50 and 51.

No. 36. *C. immunis.* F. II. About three inches long. Kept in laboratory in second-form condition eight days. May 5, 1901.

Two anterior lobes sectioned. Condition much the same as in No. 21. Spermatocytes perhaps somewhat more numerous, and spermatogonial region more extensive.

No. 37. *C. immunis.* F. II. About three inches long. Had been kept in the laboratory. Had been in second-form condition at least ten days. May —, 1901.

One lobe sectioned. In this specimen nearly all the spermatogonia have gone over into early spermatocytes. The region of spermatocytes is proportionately considerably larger than the spermatogonial region in any of the above-mentioned material. The vas deferens is well filled with spermatozoa.

From an examination of Nos. 1 to 18 it will be seen that no constant differences can be demonstrated between the testes of first- and second-form males collected in the late summer. The material examined includes specimens yet comparatively soft from exuviation as well as those which have apparently been in first- or second-form for a considerable length of time. An examination of Nos. 21 to 37 shows that in the spring ecdysis, as well, no definite difference which might determine the time of the change of form is to be observed.

The list of material described above tends to show that the main part of the regeneration of the male sexual elements takes place between the spring exuviation, in which the animal assumes the second-form, and late in August, and that during the latter portion of this period the animal may be in either of the forms. The later stages of regeneration take place, so far as I have been able to observe, in exactly the same manner, whether the animal is first- or second-form.

While advancing this theory rather tentatively, it seems to me that from the evidence at hand we must conclude that the second-form represents the period in which the greater part of the regeneration of

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the sexual elements takes place, but that the limits of this period are not definitely determined by the condition of development of the germ-cells. In other words, the *sexual* condition of the animal is not the only determining factor to be taken into consideration. This is well shown by the variation observed in the testes of individuals in the same form as well as by the similarity of those from individuals of different form, and also by the occurrence of individuals in which the alternation of forms does not regularly occur.

SUMMARY.

The principal points of this paper may be briefly summarized as follows:

1. The alternation of forms, which Faxon observed for *C. rusticus* Girard and *C. propinquus* Girard has been shown for *C. immunis* Hagen, and without doubt occurs in *C. virilis* Hagen.

2. Exceptions to this alternation of form are to be found in adult indviduals.

3. No difference can be detected between the testes of first- and second-form males taken at the same time of year, either as regards gross anatomy or microscopic structure. So far as the presence of sexual elements is concerned, therefore, the second-form male is as capable of copulation as is the first-form.

4. The second-form condition probably represents, in the adult individual, the period in which the greater part of the regeneration of the sexual elements takes place.

5. The parallel between the first- and second-form males in *Cambarus* and the spring and fall exuviation of *Astacus* is probably not without significance.

LABORATORY OF ZOOLOGY AND HISTOLOGY,
UNIVERSITY OF KANSAS, MAY 20, 1901.

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SPERMATOGENESIS OF THE MYRIAPODS.

Notes on the Spermatocytes and Spermatids of Scolopendra, I.

BY M. W. BLACKMAN.

With Plates V, VI, VII.

I.—Introduction.
II.—Material and Methods.
III.—Observations.
1. Spermatocytes.
2. Spermatids.
IV.—Comparison of Literature.
V.—Summary.
VI.—Explanation of Plates.

I.—INTRODUCTION.

In this paper it is my purpose merely to describe briefly certain appearances observed in the spermatocytes and early spermatids of *Scolopendra*, leaving the complete spermatogenesis to be treated much more at length in a future paper, which I hope soon to have ready for publication.

The terminology employed in this article will conform as closely as possible to that which has been used in other papers coming from this laboratory (by McClung[1] and Sutton[2]), but from the very extraordinary character of my material, several new terms will necessarily be introduced. These I have endeavored to make as descriptive as possible of the appearances designated.

I wish to express my gratitude to Prof. C. E. McClung for advice and assistance in carrying on this work. My thanks are due also to Mr. W. S. Sutton for collecting the material upon which these observations were made, and for various suggestions at different times.

II.—MATERIAL AND METHODS.

The material upon which these observations were made was collected in June, 1900, in Russell county, Kansas, by Mr. W. S. Sutton. The preceding spring, however, some material from other forms of myriopods was obtained by Prof. C. E. McClung. This included several species of both diplopods and chilopods. However, as the form collected by Mr. Sutton proved more favorable, the greater part of these observations was made upon it.

The species in question is the large reddish-brown *Scolopendra*,

1. McClung, C. E., 1899: "A Peculiar Nuclear Element in the Male Reproductive Cells of Insects," Zool. Bull., vol. II, No. 4. Also, same author, 1900: "The Spermatocyte Divisions of the Acrididæ," Kan. Univ. Quar., vol. IX, No. 1.

2. Sutton, W. S., 1900: "The Spermatogonial Divisions in Brachystola magna," Kan. Univ. Quar., vol. IX, No. 2.

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found abundantly in the Southwest. It is a large centipede, about four inches long and four lines across.

Each part of the paired testes, which lie in the dorsal region, consists of a number of divisions. As a rule these divisions are made up of two follicles, tapering toward each end, placed side by side in such a way that they roughly resemble a diatom. Occasionally, however, they are single; *i. e.*, they consist of only one follicle. The lobes are connected to the vas deferens by a duct attached to one end of each follicle.

The testes which I have thus far examined are far advanced in development and contain very few spermatogonia. The other generations of the germ-cell are, however, very well represented.

The younger spermatocytes, with a few spermatogonia, are arranged upon the periphery of the follicle, while within are the later spermatocytes and spermatids; and, in the central portion, are large masses of later spermatids and spermatozoa in various stages of formation. In most of the testes examined the spermatozoa are much more numerous than any of the other cell generations.

In the manipulation of this material two fixing reagents were used: Flemming's chrom-osmium-acetic mixture and Gilson's nitro-acetic-sublimate mixture. Both of these fixatives gave excellent results, but Gilson's fluid was the better. The fixation with this was perfect, there being no shrinkage or other apparent distortions.

Indeed, the only disadvantage of the Gilson fixative is the difficulty experienced in the later manipulation. When embedded in paraffin, the material is so soft and spongy that it folds upon the knife in cutting. This difficulty was obviated in the following manner: The material was gradually carried up to absolute alcohol, from which it was transferred to celloidin and allowed to infiltrate thoroughly. Then the celloidin was allowed to evaporate gradually, until it was of the consistency of thick cream. Finally all the surplus celloidin was removed, and the mass was cleared for several hours in chloroform. This accomplished, the specimen was infiltrated with paraffin and embedded in the same substance. The material cut perfectly, without any wrinkling or distortion of the sections, and without any of that shrinkage of the cells which often occurs when the ordinary paraffin method is employed.

In staining, a considerable number of reagents were employed. The best results were obtained with Heidenhain's iron-hæmatoxylin, used either alone or in connection with Congo red; Kernschwarz; and the Flemming three-color stain. Fair results were obtained also with Bismarck brown, methyl-green, cyanin, and Auerbach's methyl-green and acid fuchsin.

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III.—OBSERVATIONS.

1. *The Spermatocytes.* The spermatocytes, as they arise from the telophase of the last spermatogonial division, are very small in comparison with the truly enormous size attained by them later. Even in this stage their size varies somewhat, but the average diameter is not more than ten micra. At this time the nucleus fills nearly the entire body of the cell, and its chromatin is in the form of a number of short, granular segments. (Fig. 1.)

These segments, by their disintegration and subsequent union, form the spireme seen in a later stage. (Fig. 2.) This spireme is similar in all respects to that found in the spermatocytes of insects at the same stage of the prophase.

The resemblance of the spermatocytes of myriapods to those of insects is still further emphasized by the presence, within the nuclear cavity, of that peculiar chromatic element known as the accessory chromosome.

As is the case in insects, this element lies immediately against the nuclear membrane. It stains intensely with all chromatin reagents employed, and in other ways behaves as does the accessory chromosome of insects. It is peculiar, however, in that it is approximately spherical in form.

At this stage, the cytoplasm, although much more voluminous than in the spermatogonia, is relatively small in amount as compared with what it becomes later. It is finely reticular in structure and, as far as observed, contains no centrosome or idiozome. Yolk material is sometimes present in small quantities.

When the cell has reached the stage represented in fig. 2, the chromatin spireme gradually breaks down, and the nucleus is filled with a looser, less densely staining reticulum, as represented in fig. 3. This reticulum continues to become finer and less dense, until the cell finally reaches the stage represented in fig. 4, where the nuclear cavity is filled with a beautiful regular network composed of faintly staining fibers. Most of the cells remain in this condition until the active prophase begins with the formation of the tetrads. Some, however, go still farther, and in these the reticulum of the nucleus could not be distinguished from that of the cytoplasm were it not for the nuclear membrane enclosing it. These cells are, moreover, larger than the ordinary ones at this stage.

Meanwhile the accessory chromosome has undergone very marked changes. It has increased in size much out of proportion to the rest of the nucleus, as is shown in fig. 4. It is still approximately spherical in form and shows the same affinity for chromatin stains which is characteristic of it in preceding stages.

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Synchronously with these changes in the character of the nucleus, the cell has undergone a truly remarkable increase in size. In the early spireme stage the average diameter of the cell was about ten micra; now the average diameter is thirty-five micra, and the largest cells reach an enormous size, their diameter being about ninety micra. By this extensive growth the cytoplasm has increased in amount much more than has the nucleus (fig. 4), but still shows its finely reticular structure. Embedded in the meshes of this network are large masses of yolk material. This food substance generally forms a zone surrounding the nucleus, the inner portion being but little denser than the cytoplasm, while the outer portion, which is often broken up into uneven projections, stains much more densely. Occasionally the deutoplasm is not arranged in the manner described, but is distributed irregularly around the nucleus in masses of various sizes. At this stage I have been unable to find any centrosome or attraction sphere.

As will be seen from the plates, the spermatocyte, during this dif fuse reticular stage, approaches very nearly the egg type. Indeed, this similarity is so striking, that upon a superficial examination, I was inclined to believe that these cells were really egg-cells, and, as various stages of the male germ-cells were also present, that the animal, contrary to general belief, was hermaphrodite. However, upon further study, this first impression was soon found to be erroneous, as the true character of the cells was then conclusively apparent.

So far as I have been able to learn, male cells so very similar to the egg-cells have never been described. For that stage of the prophase in the spermatocytes of *Scolopendra* I wish to propose the name of the *pseudo-germinal-vesicle stage*. At this time the nucleus is, in appearance, identical with the typical germinal vesicle of the egg. It is small in proportion to the amount of cytoplasm, and is situated somewhat eccentrically. The reticulum is very similar in appearance to that of the immature ovum, and the accessory chromosome resembles very closely the germinal spot of the female element. Indeed, the later behavior of the accessory chromosome is very much like that of the germinal spot in those eggs in which the chromosomes are derived from this element.

From the diffuse germinal vesicle stage described, the chromatin reappears as a number of diffuse masses. These quickly assume a form identical with that of the typical insect tetrad, described by Paulmier[3] in *Anasa*, and by McClung[4] in *Hippiscus*. The process of the formation of these tetrads is so rapid that they often appear to arise from the diffuse pseudo-germinal-vesicle stage as well-defined

3. Paulmier, F. C. 1899: "The Spermatogenesis of Anasa tristis," Jour. Morph., vol. XV. Supplement.

4. McClung, C. E., 1900, loc. cit.

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tetrads, without having passed through any of the intervening stages. Several of these tetrads may often be seen in a nucleus, and among them are flaky masses of chromatin from which the rest are to be formed. In these nuclei the accessory chromosome is always irregular in form and granular toward the outside, showing that the substance from which the tetrads are formed is derived from its substance. These tetrads assume all the typical forms described for them in *Anasa* and *Hippiscus* (fig. 6), and, as in the cells of those animals, may all be referred to a single type, their apparent diversity of form being caused either by the point from which they are seen or by a slight natural modification.

The tetrads, as they first appear, are rather elongated, the longitudinal split being much more pronounced than the transverse one. At first they are composed of rather coarse granules or flakes of chromatin loosely arranged, but, as the cell approaches division, the granules become finer and arrange themselves in masses, which stain much more densely with chromatin stains. (Figs. 6, 7.)

It is at about this time that the centrosome appears. (Fig. 7.) It is first to be seen in the yolk material, which at this stage is collected in a large, irregular mass at one side of the nucleus. The centrosome is a rather prominent dumb-bell-shaped body contained in a clear space, fairly well differentiated from the surrounding deutoplasm. At this stage it is not nearly so large as it becomes later, in the prophase and in the metaphase.

From this time the movements of the centrosome can be traced clearly, up to the telophase of the succeeding division. The dumb-bell-shaped figure elongates and finally constricts (fig. 8), forming two spherical bodies. Astral radiations then appear and the centrosomes move toward the nucleus and finally come to rest upon the nuclear membrane. (Fig. 9.) The astral radiations become more marked and the centrosomes move slowly apart upon the membrane. (Figs. 9, 10, 11, 12).

When they have reached points about 100 degrees apart, the nuclear membrane begins to disappear. That part over which the centrosomes have not passed in their migration is the first to be dissolved, while the portion between the centrosomes persists for some time, as is shown by the numerous cells in which it is still to be found. (Figs. 11, 12.) At this stage the astral rays are more marked than at any preceding time, but are not so prominent as they become later, in the metaphase and anaphase.

While these phenomena have been occurring, the tetrads have also changed. They have lost their granular character and ragged outline, have become much more homogeneous, and have assumed an approximately spherical form. They can no longer be distinguished

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from the accessory chromosome, which, on account of its greater density and its nearly spherical form, could be easily observed up to this time.

Since the pseudo-germinal-vesicle stage, the accessory chromosome has undergone several interesting changes. As we have seen, it is then remarkable for its large size and strong affinity for chromatin stains. In the active prophase following this, while the chromatin is collecting in diffuse, flaky masses preparatory to tetrad formation, this element decreases much in size, and at the same time its outline becomes very irregular. In a later stage, shown in figs. 5, 9, the contour of this element has again become regular; it has resumed its spherical form, and has diminished in size, until now it is no larger than a chromosome in the metaphase of the first spermatocyte division. It goes to the equatorial plate without previously showing any sign of division.

I can see but one plausible explanation for the behavior of the accessory chromosome in the pseudo-germinal-vesicle stage and in the late prophase succeeding. While the nucleus is in the diffuse condition, it would seem that the accessory chromosome acts as a storehouse for practically all of the chromatin of the cell, or, more properly, serves as a center around which the chromatin becomes condensed. As has been mentioned before, the later behavior is very similar to that of the germinal spot in some eggs.

With the disappearance of the nuclear membrane, mantle fibers are seen connecting each centrosome with the chromosomes. (Fig. 11.) The chromosomes heretofore distributed irregularly throughout the nuclear space are drawn into the equatorial plate, and a very short spindle is formed. (Fig. 13.)

Later the centrosomes move apart some distance, until the cell presents the appearance represented in fig. 15. By this movement the shape of the chromosomes is altered somewhat, and they now show signs of division. At this stage the astral rays can be seen, connecting the centrosomes with the cell membrane. They are very distinct, and there is no question but what they really extend from the centrosome to the cell membrane. From their separation upon the nuclear membrane, up to this time, the centrosomes have been of an irregular spherical form. Now, however, their shape is changed, and they appear as rather large, cone-shaped masses, with their apices turned toward the equatorial plate. (Figs. 15, 16.) At no time is the outline of the centrosome exactly spherical.

When the cell has reached this stage a very unusual thing occurs. By the contraction of the astral rays attached to the cell membrane the centrosomes are drawn still farther apart, and take up their position at points a short distance from the cell membrane. (Fig. 16.)

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The peculiar thing is that the mantle fibers no longer converge toward the centrosomes, but to the points which the centrosomes occupied before their last migration. From this center of convergence, which I will call *the apical point*, parallel strands of linin extend to the centrosome. These linin bands are, I believe, but the continuation of the mantle fibers. Radiating fibers are now seen extending out into the cytoplasm, from the apical point as well as from the centrosome proper, although those from the latter are much more distinct. The astral rays connecting the centrosome and the cell membrane are still more pronounced at this stage. The centrosome is still conical in form.

The centrosomes again move apart and take up their final position upon the cell membrane, where they are flattened out into rather large hemispherical bodies. Well-marked astral radiations still extend out into the cytoplasm. By these last movements of the centrosomes the chromosomes have been drawn apart, and, by the synchronous contraction of the mantle fibers, have been drawn toward the poles, and come to rest at the point at which the mantle fibers converge, where they are arranged in a densely packed mass. (Fig. 17.)

When the chromosomes have taken up their final positions the cell-walls begin to constrict. As this proceeds the fibers connecting the two daughter masses of chromatin are crowded together into a bundle, which finally presents the appearance represented in fig. 20. A midbody, or zwischenkörper, is formed at the point where the constricting wall approaches this bundle of persisting fibers. This is composed of a number of small, darkly staining bodies about equal in number to the chromosomes. These bodies are arranged close together upon the periphery of the bundle in such a manner as to form a ring. (Fig. 20.) A similar appearance has been described by McGregor[5] in *Amphiuma*. In *Scolopendra*, however, this ring does not persist, as is the case in *Amphiuma*.

The division figures of the second spermatocytes are very similar to those of the first. Indeed, the two generations can be distinguished only by the character of the chromosomes. A short spindle is formed (fig. 21), and the cell undergoes changes similar to those in the first spermatocytes. In the early telophase the cell presents the appearance represented in fig. 22. The daughter masses of chromatin are smaller than in the corresponding stage of the first division. The chromosomes are so closely massed together that the outlines of the individual elements cannot be distinguished, although, of course, they do not lose their individuality. Connecting fibers extending from one daughter plate to another are plainly visible, and astral radiations

5. McGregor, J. H.: "The Spermatogenesis of Amphiuma," Jour. Morph., vol. XV. Supplement.

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are also to be seen proceeding out into the cytoplasm. The centrosomes are rather large, hemispherical bodies, in close contact with the cell-wall. Midway between the daughter plates the cell membrane shows evident signs of constriction.

In a later stage, shown in fig. 23, the cell membrane constricts in the plane of division, and, as this advances toward the center of the cell, the fibers persisting between the daughter masses of chromatin are crowded together so as to form the well-known spindle remains. A midbody is formed, as in the telophase of the first spermatocytes. The centrosomes still persist, although they have diminished in size, and the astral radiations have disappeared. They are still to be found in close contact with the cell membrane at the ends of the cell furthest from the plane of division. The cytopasm has resumed its reticular character. The last trace of yolk material disappeared at about the time of the disintegration of the nuclear wall in the first spermatocytes (fig. 12), and none has yet reappeared. The chromosomes have become separated from each other and are irregularly distributed throughout the nuclear vesicle, which at this time is surrounded by no well-defined membrane. At this stage they still preserve their regular outlines.

2. *The Spermatids.* The spermatids, as they arise from the last maturation division, are rather small cells, with the nucleus placed somewhat eccentrically. Fig. 24 represents one cut through the short diameter of the cell. The cell membrane is fairly well defined and the nucleus is spherical in shape, as usual. At first the chromosomes are regular in outline but soon break down, and the nucleus is occupied by a number of irregular chromatin masses. Linin fibers can be seen connecting the chromatin masses.

When the cell has reached this stage a very remarkable thing happens. The nuclear wall sends out a projection upon one side (fig. 25), and into this protuberance, which is still surrounded by the well-defined nuclear membrane, several of the irregular chromatin masses pass. These are still connected with each other, and with the other masses of chromatin in the nucleus, by linin fibers. The number of these masses which pass into this bud or protuberance varies somewhat, but is generally two or three.

This protuberance soon shows signs of constricting off from the main body of the nucleus (fig. 26), and at this period the nucleus presents much the appearance of a yeast cell during the process of budding. This body, for which I would propose the name of *itomere* (the word indicating the behavior of this body), becomes constricted off from the nucleus, and, moving out through the cytoplasm, finally passes through the cell membrane and is extruded from the cell. Various stages in the migration of this peculiar structure are repre-

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sented in figs. 25 to 30. In fig. 26 the itomere has nearly constricted off from the nucleus. In fig. 27 it has left the nucleus and is seen free in the cytoplasm, surrounded by a rather well-defined membrane. The nuclear membrane remains open at the point from which it was constricted, and the course the itomere has taken through the cytoplasm is plainly visible. In fig. 28 it is seen extending from the nucleus, with which it is still connected, to the cell membrane. In fig. 28 it has reached the cell membrane, and in fig. 29 has been extruded and the membrane has apparently closed behind it.

In all these cases the nucleus has remained open, and the pathway left by the itomere in its passage through the cytoplasm can be plainly distinguished. The best stain for demonstrating the stages just described is obtained by using Heidenhain's iron-hæmatoxylin in connection with Congo red. The chromatin, as usual, takes on a dense black stain, that of the nucleus and that of the itomere staining precisely alike. The ground substance of the cytoplasm takes on a transparent red stain, against which the fibers forming the reticulum stand out plainly. The pathway left by the itomere stains a little darker red than the groundwork of the reticulum.

The budding process and the extrusion of the itomere is accompanied and succeeded by a great increase in the size of the cell, as can plainly be seen by consulting the plates. At first this growth is more marked in the cytoplasm (figs. 24–27), but later the nucleus also grows, although not in proportion to the cytoplasm. (Figs. 29–31.) As far as I am informed, such a remarkable increase in the amount of cytoplasm has never been described in the spermatids.

During this growth period masses of deutoplasm are present in the cells in more or less abundance. The first evidence of yolk observed in the spermatids appears at the time of the protrusion of the itomere.

Thus the formation and extrusion of the itomere seem to have some connection with the succeeding growth of the cell and the appearance of yolk substance, as well as with the origin of another structure concerning which I shall speak later.

I wish now to return to a consideration of the behavior of the centrosome. The last time the centrosome was mentioned it was a rather small, darkly staining body, in close contact with the cell membrane, upon that side of the cell farthest from the plane of division. At this time no radiations are to be seen proceeding from it and it is surrounded by no idiozome or attraction sphere. From this place the centrosome can be traced for a time, but is lost. Later it reappears, and from this time can be traced to its final position in the middle piece of the spermatozoön. It leaves its place upon the membrane and, up to a time when the budding process is well under way, may be seen at various places in the cytoplasm. There it disappears and is not again

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seen until the stage represented in fig. 30 is reached, when it has taken up its position near the nucleus, at one side of the opening in the nuclear membrane. At the time of the disappearance of the centrosome, masses of deutoplasm have become abundant in the cell, and it is very probable that this element is merely concealed by one of these and that it will be found on further study.

As before stated, the pathway left by the itomere in its passage through the cytoplasm can be easily distinguished. As the cell increases in size, this, instead of becoming more faint, as one might expect, gradually becomes plainer and more easily distinguishable (figs. 29–33), until, in the stage represented in fig. 34, it stands out as a densely staining black line—the axial filament. This is formed, not by an outgrowth or elongation of the centrosome, as has been described for other objects, but by the collection and condensation of the fibers of the cytoplasmic reticulum. In earlier stages (fig. 32), a cross-section of the pathway left by the itomere shows a rather diffusely staining area, toward which the fibers composing the reticulum converge as toward a centrosome. At this stage, however, the centrosome can be clearly distinguished at a point near the nucleus and at one side of the position subsequently occupied by the axial filament. Later, it moves directly into the course of the future axial filament, which, at this period, stains more densely, and, although still somewhat granular and indefinite in appearance, stands out much more distinctly than at any previous time. (Figs. 33, 34.)

While this is taking place the cytoplasm becomes vacuolated in the region surrounding the axial filament. The large, rather elongated vacuoles extend with their longer diameters approximately parallel to the course of this structure.

The significance of this vacuolation appears to be in the fact that the previously fine reticulum is being broken down and reformed into fibers extending parallel to the axial filament, thus leaving large clear spaces in the cytoplasm. In later stages these fibers become collected and condensed, and in the mature spermatozoön, although they still preserve their individuality, cannot be distinguished from each other without the aid of maceration. The origin of the axial filament in *Scolopendra* from the fibrillar reticulum of the cytoplasm agrees with the discoveries by Ballowitz[6] of the fibrillar character of this element in spermatozoa. He describes it as being made up of a large number of parallel fibrillæ.

The axial filament being thus definitely formed, farther changes consist in its elongation, and this continues until it is several hundred micra in length. Its later growth is accompanied by a corresponding

6. Ballowitz, E., 1891: "Weitere Beobachtungen uber den feineren Bau der Saugethierspermatozoen." Zeitschrift fur wissenschaftliche Zoologie. Bd. LII.

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lengthening of the cell. When the spermatid has reached the stage shown in fig. 35, the cell outline in the region posterior to the nucleus is very difficult to follow.

An acrosome first appears at this stage, at the side of the nucleus opposite the base of the axial filament. This, at this time, is a spatulate vacuole, which shows no affinity for chromatin stains. In later stages this body increases much in size and stains weakly with iron-hæmatoxylin. (Figs. 38, 39.)

Concerning the later changes in the spermatid I will say nothing in this paper, but will merely show a few of the observed stages by drawings.

IV.— COMPARISON OF LITERATURE.

The Accessory Chromosome.—Until quite recently the true nature of the accessory chromosome was not understood, and by various writers it has been classified among that very ill-defined group of bodies, the nucleoli. It was first observed by Henking,[7] and by him called a nucleolus. Later observers, Vom Rath,[8] Wilcox,[9] Moore,[10] and Wagner,[11] have evidently had much the same understanding of its nature, as they classified it similarly. In 1898 Montgomery[12] found the same element in the testicular cells of *Pentatoma*, but evidently did not fully understand its true character, as he called it the "chromatin nucleolus."

In 1898 McClung[13] first correctly interpreted the character of this element. He described it as a metamorphosed chromosome, and to it applied the name "accessory chromosome."

In a paper which appeared the latter part of the same year, Paulmier[14] recognized its chromosomal nature and designated it the "small chromosome." This name appears to have been unfortunately chosen, as in many animals this element is the largest and most conspicuous chromosome in the cells. In his material, *Anasa tristis*, the accessory chromosome takes on the shape of a completely formed tetrad without passing through any of the preceding stages. In the first spermatocyte division it is divided along with the other chromosomes, but in the second, after remaining in the equatorial plate for some time, goes to one pole undivided.

7. Henking, H., 1891: "Ueber Spermatogenese und deren Beziehung zur Entwicklung bei Pyrrhocoris apterus." Zeitsch. f. Wissensch. Zool. Bd. XXV.

8. Vom Rath, O., 1892: "Zur Kenntniss der Spermatogenese von Gryllotalpa vulgaris." Archiv f. Mikro. Anat., Bd. XI.

9. Wilcox, E. V., 1895: "Spermatogenesis of Caloptenus femur-rubrum and Cicada tibicen." Bull. Mus. Comp. Zool., vol. XXVII.

10. Moore, J. E. S.: "On the Structural Changes in the Reproductive Cells during the Spermatogenesis of Elasmobranchs." Quart. Journ. Micr. Sci., vol. XXXVIII.

11. Wagner, J., 1896: "Beitrage zur Kenntniss der Spermatogenese bei den Spinnen." Arb. Nat. Ges., St. Petersburg, vol. XXVI.

12. Montgomery, T. H., jr., 1898: The Spermatogenesis of Pentatoma up to the Formation of the Spermatid." Zool. Jahrb. Bd. XII.

13. McClung, C. E., 1899, loc. cit.

14. Paulmier, F. C., 1899, loc. cit.

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McClung,[15] in a later paper, describes the accessory chromosome as occurring in *Hippiscus*. In the spireme stage it is to be seen as a large, densely staining homogeneous body, in close contact with the nuclear membrane. In a later stage it leaves its peripheral position and takes on the appearance of a longitudinally split rod. It is divided by the first maturation mitosis, but in the second passes over bodily into one of the daughter cells. In *Scolopendra*, as far as I have observed, the accessory chromosome shows no sign of division in the prophase and goes to the equatorial plate as a spherical body.

Sutton,[16] in his article on "The Spermatogonial Divisions in *Brachystola magna*," describes the behavior of this element in the spermatogonia. He throws much stress on the individuality of this element, for, as he conclusively shows, "It maintains throughout the spermatogonial divisions, as well as those which follow, an indubitable independence, being enclosed at all stages, except those of actual division, in its own individual membrane." As I have shown, quite a different condition exists in the pseudo-germinal-vesicle stage of *Scolopendra*, for at this stage all the chromatin of the cell is condensed into one deeply staining, homogeneous mass.

Montgomery,[17] in his article on *Peripatus*, fails to find an accessory chromosome, but describes a body which behaves very much like this element. He gives at length his reasons for not considering it the "chromatin nucleus." However, I believe he is mistaken, and that the element described is, in truth, the accessory chromosome.

In comparing the accessory chromosome found in *Scolopendra* with that described by these investigators, several points of difference are observed as well as many points of similarity. Its origin, staining reaction and its behavior in the early spermatocytes are very similar to that in insects, but in its behavior in the pseudo-germinal-vesicle stage, and in the succeeding stages, it is quite different. As I have shown, it seems to act as a reservoir in which is deposited practically all of the chromatin of the nucleus. At this stage it is enormous as compared with its former size. In the later prophase, part of the chromatin forming this mass leaves the accessory chromosome and collects in diffuse granular masses, which eventually form the tetrads as described. At this time the accessory chromosome loses its regular outline and becomes granular toward the outside. When the tetrads are formed, however, it again assumes its homogeneous character and regular outline, but has decreased in size until it is no larger than the ordinary chromosome in the metaphase. It can be readily distinguished from the other chromosomes up to the time of the dis-

15. McClung, C. E., 1900, loc. cit.

16. Sutton, W. S., 1900, loc. cit.

17. Montgomery, T. H., jr., 1901: "The Spermatogenesis of Peripatus up to the Formation of the Spermatid." Anat. An. Bd. XVI.

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integration of the nuclear membrane. It goes to the equator without previous sign of division.

Tetrad Formation. The typical process of tetrad formation in insects, as described by Paulmier[18] in *Anasa* and McClung[19] in *Hippiscus*, is as follows: The spireme splits lengthwise and segments into a number of rods equal to the maturation number of chromosomes. These double rods shorten, become more finely granular, and split again transversely. At this time the typical form is represented by the cross-like figures shown in the plates (figs. 5, 6, 7), although there are many modifications. These cruciform masses condense, become homogeneous, and stain more transparently.

I have already described the process of tetrad formation in *Scolopendra*. In the formation of the tetrads from the diffuse, flaky mass of chromatin arising in the pseudo-germinal-vesicle stage there seems to be no definite splitting of the segment, but the chromatin seems to collect more densely at certain areas, and thus to form the tetrad figures.

As regards the sequence of the longitudinal and cross divisions of the chromosomes, there seems to be much difference in the results of various investigators on arthropods. Several observers, among whom are Vom Rath,[20] Paulmier,[21] and Montgomery,[22] describe the transverse division as occurring first. Häcker[23] and McClung,[24] however, find that the first is the equation and the second the reduction division. McClung lays especial stress upon the importance of the later prophase of the spermatocyte in determining the sequence of the following divisions. His point seems to be very well taken, and, as in *Scolopendra*, as well as in *Hippiscus*, the longitudinal cleavage is the first one made manifest in the prophase. I believe that the first mitosis results in the longitudinal division of the tetrads.

The Budding of the Nucleus. In the male germ-cell, nothing has been described, I believe, which corresponds to that peculiar structure which I have called the itomere. In the egg-cells of various animals, however, a structure, similar in origin and, in some respects, in function, has been reported by several investigators. This is the yolk nucleus, as described by Blochmann, Scharff, Balbiani, and others.[25] In the material upon which these investigators worked, the yolk nucleus is derived from the chromatin reticulum of the nucleus

18. Paulmier, F. C., 1899, loc. cit.
19. McClung, C. E. 1900, loc. cit.
20. Vom Rath, O., 1892, loc. cit.
21. Paulmier, F. C., 1899, loc. cit.
22. Montgomery, T. H., jr., 1898 and 1901, loc. cit.
23. Hacker, V., 1897; "Ueber weitere Uebereinstimmungen zwischen den Fortpflanzungsvorgangen der Thelre und Pflanzen." Biol. Cent., vol. 17.
24. McClung, C. E., 1900, loc. cit.
25. Wilson, E. B., 1900: "The Cell in Development and Inheritance."

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by the process of budding. A protuberance appears upon the nucleus, is constricted off, and, passing out into the cytoplasm, serves as a center around which the food substance of the cell is formed.

Thus, although the origin is similar in some respects to that I have described for the itomere in the spermatids of *Scolopendra*, its later behavior is very different. The itomere migrates through the cytoplasm, and is cast out through the cell-wall. The movement of this structure through the cytoplasm is accompanied by the formation of yolk material and the rapid growth of the cell, but its most important function is quite different. In its migration toward the cell-wall it seems to organize the cytoplasm and to mark out the course of the future axial filament.

The Origin of the Axial Filament. Regarding the origin of the axial filament there seems to be much unanimity of opinion among the more recent investigators. In 1895 Moore[26] found that, in elasmobranchs, the axial filament is formed by the elongation of the centrosome. Quite similar results were obtained by other investigators on the elasmobranchs, and in mammals and amphibians a like origin is ascribed to this element.

As regards its formation in arthropods, Paulmier[27], in *Anasa*, speaks of the axial filament as an outgrowth of the centrosome. Whether by this he means that, beginning with the centrosome at the base of the nucleus, the cytoplasmic reticulum is progressively condensed, or whether he believes it to be formed by a mere elongation of the centrosome, as in elasmobranchs, I cannot determine.

In either case its origin does not correspond to that in *Scolopendra*. In this material it certainly is not an elongation of the centrosome, and, just as surely, is not a progressive condensation of the cytoplasmic reticulum, for at all stages all parts of the axial filament stain exactly alike. In my observations I have attempted to explain the true origin of this structure, and it will not be necessary to repeat it here.

V.—SUMMARY.

1. The spermatocytes, as they arise from the diffuse stage succeeding the telophase of the last spermatogonial division, are small cells with very little cytoplasm, the nucleus filling nearly the entire cell body. The chromatin, with the exception of the accessory chromosome, becomes arranged in a spireme, and the proportional amount of cytoplasm is much increased.

2. The spireme breaks down, and a fine, weakly staining reticulum is formed. This becomes finer and less prominent until it is no stronger than the cytoplasmic reticulum. Meanwhile the accessory chromo-

26. Moore, J. E. S., 1895, loc. cit.
27. Paulmier, F. C., 1899, loc. cit.

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some has increased enormously in size, much out of proportion to the rest of the nucleus.

3. At this stage the appearance of the nucleus corresponds very closely to that of the germinal vesicle in the egg-cell. The cytoplasm has greatly increased, and large masses of yolk substance have appeared, surrounding the nucleus. On account of these characteristics this stage has been called the pseudo-germinal-vesicle stage.

4. The chromatin appears after the pseudo-germinal-vesicle stage in the form of diffuse masses of chromatin, which quickly take on the cruciform shape characteristic of the typical insect tetrad.

5. At the time of the formation of the tetrads, the accessory chromosome has decreased much in size and its outline has become irregular. Later it again becomes spherical, and at this period is of about the size of a chromosome in the metaphase.

6. Soon after the formation of the tetrads, the centrosome appears in the mass of deutoplasm as a dumb-bell-shaped body. It moves toward the nucleus, separates, astral rays are developed, and the centrosomes move apart upon the membrane. When they have reached points about 100 degrees apart the nuclear membrane disintegrates, and the chromosomes are drawn into the equatorial plate. That part of the membrane over which the centrosomes have not passed disappears first, the rest persisting for some time.

7. The accessory chromosome, freed of its surplus chromatin, can be distinguished up to the disappearance of the nuclear membrane, when it is drawn into the plate with the other chromosomes. It has previously shown no sign of division.

8. The short spindle thus formed lengthens, and the chromosomes are drawn more into the equatorial plate. Astral rays may be distinctly seen connecting the centrosomes and the cell membrane. The centrosomes move apart again to a point a short distance from the cell-wall. The mantle fibers no longer converge toward the centrosomes, but toward the point (the apical point) occupied by them before their last migration. Between the apical points and the centrosomes the mantle fibers are drawn out into parallel threads. At this time the centrosomes have changed their form to that of a cone, with their apices directed toward the point of the spindle.

9. By the contraction of the astral rays the centrosomes are drawn to the cell-wall, where they are flattened out into hemispherical bodies. Synchronously the mantle fibers contract, the chromosomes are separated, and the two daughter groups are drawn toward the poles and take up their final positions at the apical point.

10. The second spermatocytes can be distinguished from the first only by the shape and size of the chromosomes.

11. Soon after the formation of the membrane, after the last ma-

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turation division, a portion of the nucleus buds off, and, passing through the cytoplasm, is extruded from the cell. This is the itomere.

12. The protrusion and casting out of the itomere is accompanied and succeeded by the formation of yolk masses and by a great increase in the size of the cell.

13. The pathway left by the itomere, on its passage through the cytoplasm, persists and becomes stronger as the cell advances in development. It marks out the course later taken by the axial filament.

14. The axial filament is not formed by an elongation or outgrowth of the centrosome, but by the condensation of the cytoplasmic reticulum, along the line marked out by the itomere in its passage to the cell wall.

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PLATE V.

NOTE.—All drawings were made by the author, with the aid of a camera lucida. A Bausch & Lomb one-twelfth-inch objective and one-inch eyepiece were used. Length of tube, 165 mm.; camera lucida arm., 95 mm.; magnification, about 1000 diameters. Drawings not reduced in reproduction.

FIG. 1. Early spermatocyte, showing small size of cell and relatively large size of nucleus.

FIG. 2. Later stage. The chromatin in the spireme condition. The cell has grown somewhat and the amount of cytoplasm especially has increased. The dark body at one side of the nuclear cavity is the accessory chromosome.

FIG. 3. Considerably later stage. Cell has increased in size. The spireme is broken down and stains diffusely. The accessory chromosome has increased much in size. Yolk masses in a halo around the nucleus.

FIG. 4. The *pseudo-germinal-vesicle stage*. The chromatin, with exception of accessory chromosome, arranged in a diffuse reticulum. The accessory chromosome is at its maximum size and contains practically all the chromatin of the nucleus.

FIG. 5. The chromatin is reappearing in the form of tetrads. The accessory chromosome has decreased much in size. Yolk mass at one side of nucleus.

FIG. 6. Later stage in tetrad formation, showing several modifications of the typical form.

FIG. 7. Later prophase. Tetrads shorter and more massed. Accessory chromosome plainly distinguishable. Centrosome first seen at this stage as a dumb-bell-shaped figure in the mass of dentoplasm.

FIG. 8. The centrosome has moved toward the nucleus. Astral rays have formed.

FIG. 9. The centrosomes have reached the membrane and, having separated, have begun their migration apart.

FIG. 10. Centrosomes still further apart.

FIG. 11. Late prophase. The membrane has partly disappeared and the mantle fibers are seen connecting the centrosomes and chromosomes.

FIG. 12. Stage somewhat earlier than fig. 11.

FIG. 13. Later stage, showing the short spindle. Chromosomes are arranged in the equator. Astral rays are seen extending to the cell membrane.

FIG. 14. The spindle has elongated and the chromosomes show signs of division.

FIG. 15. Slightly later stage.

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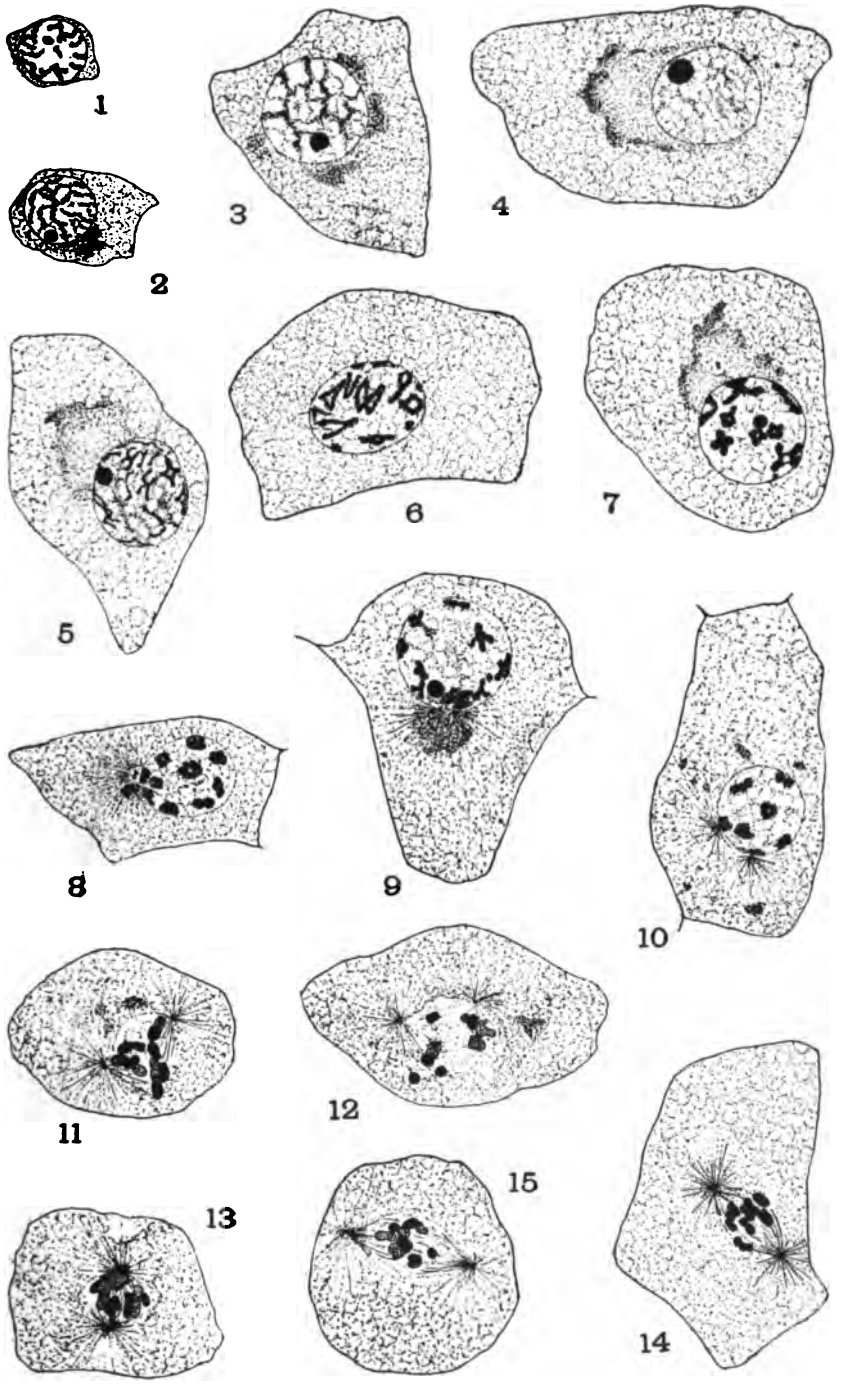

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PLATE VI.

FIG. 16. Later metaphase, showing peculiar character of spindle, with the mantle fibers converging at the *apical point*. Centrosomes are conical in shape. Astral rays connect centrosome and cell membrane.

FIG. 17. Early telophase of first spermatocyte division, showing the position of the daughter groups of chromosomes. The centrosomes are hemispherical in shape and are flattened against the cell membrane.

FIG. 18. Later telophase, showing division membrane. The section is cut in such a plane that the persisting spindle remains do not show.

FIG. 19. Polar view of telophase of first spermatocyte.

FIG. 20. Telophase showing persisting spindle remains. Midbody in the form of a ring.

FIG. 21. Metaphase of second spermatocyte division.

FIG. 22. Telophase of second spermatocyte. The cell-wall shows signs of constriction.

FIG. 23. Later telophase. The chromosomes are distributed throughout the nuclear vesicle. Spindle remains persist. Centrosomes still on the cell membrane.

FIG. 24. Early spermatid.

FIG. 25. Later stage, showing the protuberance upon one side of the nucleus preparatory to the constriction of the *itomere*.

FIG. 26. Later stage in the protrusion of the itomere.

FIG. 27. Still later stage, with the itomere in the cytoplasm midway between the nucleus and the cell-wall.

FIG. 28. Cell, showing the itomere extending from the nucleus to the cell-wall.

FIG. 29. Stage showing the itomere near the cell-wall. The pathway left by it in its passage through the cytoplasm is plainly visible.

FIG. 30. Later stage, showing the itomere extruded from the cell. Its course through the cytoplasm is still to be seen. The nucleus is still open at the place of constriction. The centrosome is seen upon one side of the opening. The cell has increased much in size.

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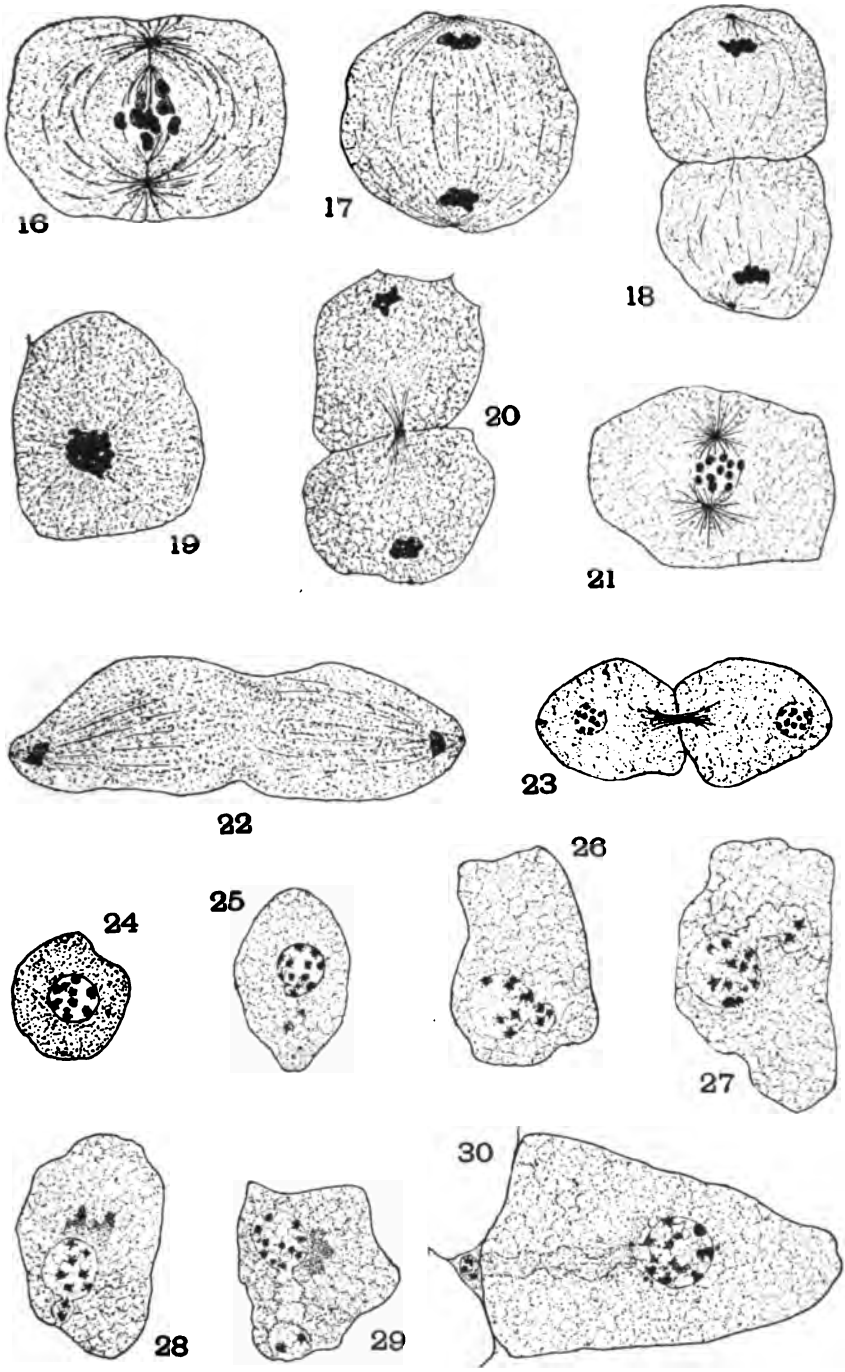

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PLATE VII.

FIG. 31. Considerably later stage. The itomere has disappeared. The cell has grown much in size. The path left by the itomere is more marked than before.

FIG. 32. About the same stage, showing a cross-section of the forming axial filament, with the fibers of the cytoplasmic reticulum radiating from it.

FIG. 33. Later stage. The axial filament more nearly formed. The centrosome has moved nearer its base.

FIG. 34. Later stage in the formation of the axial filament. The cell has begun to elongate. The cytoplasm is broken up into elongated vacuoles extending parallel to the axial filament.

FIG. 35. Much later stage. The cell body has elongated a great deal. The membrane of the posterior part of the cell has disappeared. On the side of the nucleus opposite the insertion of the axial filament there is a large transparent acrosome. At this stage the nucleus has reached its greatest size.

FIG. 36. About the same stage of a smaller cell. Acrosome not shown in the section.

FIG. 37. The nucleus has become condensed and elongated. The acrosome stains more densely. The cytoplasm contains strands of linin extending parallel to the axial filament.

FIG. 38. The nucleus has become still further condensed and has elongated considerably. Acrosome stains darker.

FIG. 39. The nucleus is still more condensed and takes a black stain. Acrosome also stains more strongly.

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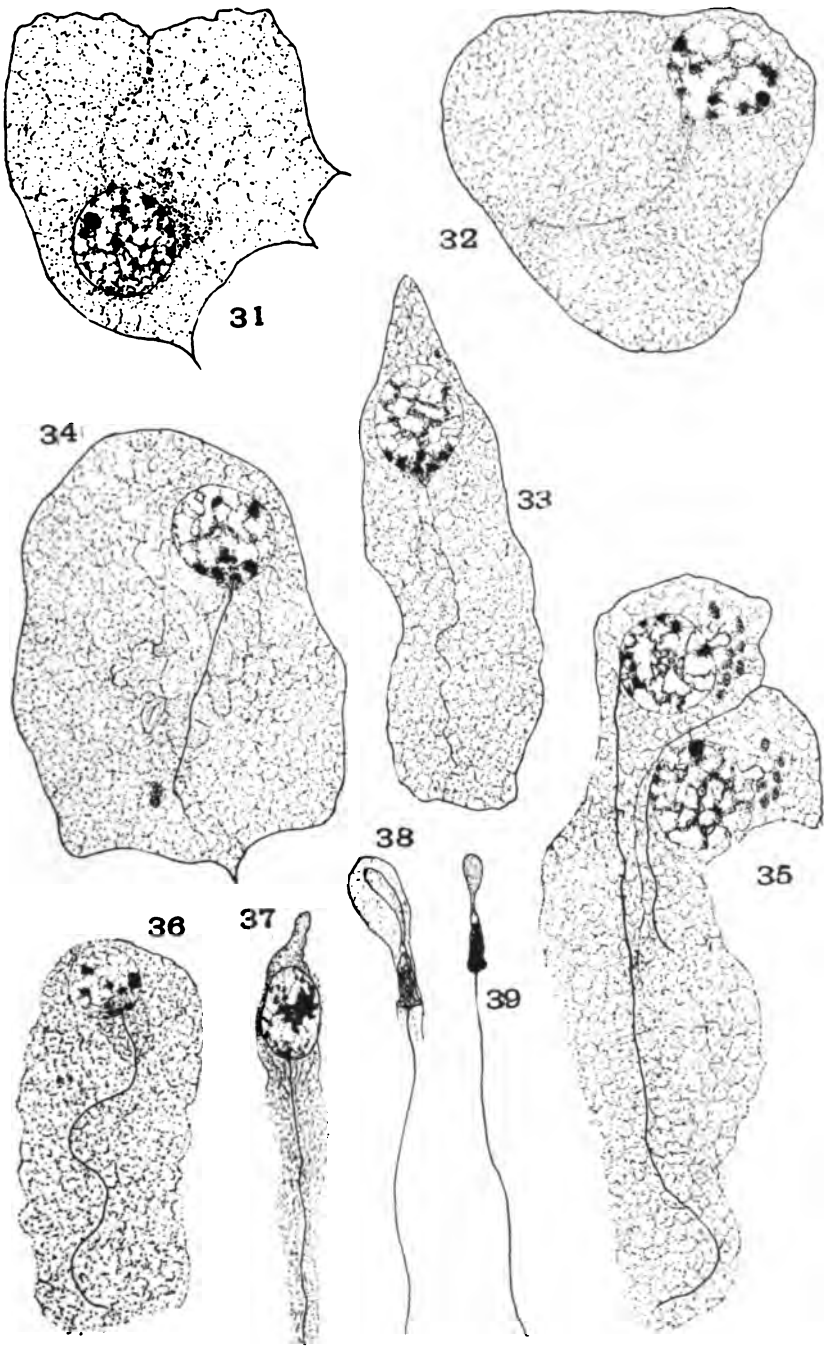

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THE

KANSAS UNIVERSITY QUARTERLY.

(Vol. X, No. 3—July, 1901.)

SERIES A.—SCIENCE AND MATHEMATICS.

CONTENTS:

I.—Action of Liquid Ammonia on Acid Chlorids and Esters, *Edward Bartow* and *David F. McFarland.*

II.—A New Theory of Collineations in Space, II, *H. B. Newson.*

III.—A New Theory of Collineations in Space, III, *H. B. Newson.*

IV.—Coccidæ of Kansas, IV, ... *S. J. Hunter.*

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KANSAS UNIVERSITY QUARTERLY.

VOL. X, No. 3. JULY, 1901. SERIES A.

ACTION OF LIQUID AMMONIA ON ACID CHLORIDS AND ESTERS.

BY EDWARD BARTOW AND DAVID F. MCFARLAND.

THE product of the action of ammonia gas or an ammonium compound on an ester of an organic acid, or on an acid chlorid, is generally an acid amid. This fact is so well recognized that it is given as a general method for the preparation of acid amids. It is stated thus in Beilstein's Handbuch der Organischen Chemie, volume I, page 1232: "Die Amide entstehen bei der Einwirkung von Ammoniak auf die zusammengesetzten Aether organischer Säuren. Es ist angezeigt, bei möglichst niederer Temperatur zu arbeiten und freie Alkohole fern zu halten (Bonz, Ph. Ch. 2, 900). In der Kälte verläuft die reaction sehr langsam, rascher beim Erhitzen unter Druck. . . . Leichter erhält man die Amide beim Behandeln der Anhydride mit Ammoniak, am bequemsten aber aus den Chloriden und concentrirtem, wässerigem Ammoniak (oder trokenem Ammoniumcarbonat)."

It seems that the ammonia used for these amid syntheses has always been in the form of a gas, or combined in an ammonium compound, and that no one has published results of experiments in which *liquid* anhydrous ammonia was used as the source of the ammonia. The commercial use of liquid ammonia in the manufacture of ice has so cheapened it that it is now an adjunct to every well-equipped chemical laboratory, and it affords a convenient source of ammonia for many experiments. Its comparative purity and freedom from moisture recommend it for some syntheses, and it was particularly on account of these qualities that it seemed possible to use it for the syntheses of acid amids.

A series of experiments was undertaken, therefore, to ascertain, first, whether acid amids could be obtained by the action of liquid ammonia on acid chlorids; second, whether they could be obtained from esters; third, the conditions governing such reactions; and fourth, when amids are not formed, to ascertain what products are formed.

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The ammonia used in the following experiments was the commercial product. It was drawn directly from the cylinder into Dewar tubes, or more commonly into flasks, insulated by placing them in beakers and filling the space between the neck of the flask and the sides of the beaker with cotton. This seemed quite effective in preventing too rapid evaporation of the ammonia.

ACTION OF LIQUID AMMONIA ON ACID CHLORIDS.

The chlorids first used were those of mono-, di- and trichloracetic acids. Our experiments were carried on as follows: The chlorid was dropped slowly from a dropping funnel into a small insulated flask containing liquid ammonia. This produced a violent reaction, due not only to reactive tendencies of the two substances, but also to the great difference in their temperatures. The chlorid at the temperature of the room was fully 60° warmer than the boiling ammonia; consequently, dropping the warm chlorid into the cold ammonia caused the latter to boil violently. So violent was the reaction that dense white fumes, probably composed of a mixture of the amid and ammonium chlorid, were given off. This loss was overcome, to a large degree, by cooling the chlorid to the temperature of boiling ammonia, by immersing the vessel containing it in a bath of ammonia, and then dropping ammonia into the cooled chlorid. When the first reaction was over the mixture was treated with an excess of ammonia, which was then allowed to evaporate. The amids were then obtained pure by extracting the white residue with chloroform.

By this method the amids of the three chloracetic acids were obtained. They were identified by their characteristic melting-points, and this identification was supplemented in two of the compounds by chlorine determinations according to the method of Carius.

I. 0.1721 g. substance gave 0.3882 g. AgCl.

Calculated for dichloracetamid, $CHCl_2CONH_2$		Found.
Cl	55.41%	55.76%

II. 0.0731 g. substance gave 0.1952 g. AgCl.

Calculated for trichloracetamid, CCl_3CONH_2		Found.
Cl	65.49%	66.02%

This method, which has proved so successful in preparing chloracetamids, did not, however, succeed with acetamid itself. A similar treatment of acetyl chlorid with liquid ammonia gave a mixture which possessed the unmistakable odor of acetamid; but, thus far, our attempts to obtain *crystals* of acetamid have been unsuccessful.

With bromacetyl chlorid a white mass was obtained, which did not

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melt at 200°, but which turned red when heated or allowed to stand for some days. No amid was isolated. The only other chlorids tried in this way were benzoyl chlorid and sulfuryl chlorid. From these benzamid and sulfamid were obtained.

The chief drawback in the above method is the difficulty of freeing the amid from the ammonium chlorid which is formed at the same time. Up to this time we have been prevented from further experiments with chlorids by our lack of pure specimens. When such specimens are secured, the experiments will be continued.

ACTION OF LIQUID AMMONIA ON ESTERS.

Since the action of aqueous and alcoholic ammonia on esters of organic acids will cause the formation of amids, sometimes even in the cold, a series of experiments with liquid ammonia and the esters promised good results. The expected reaction is as follows:

$$RCOOC_2H_5 + NH_3 = RCONH_2 + C_2H_5OH$$

for the ethyl esters, and, more general,

$$RCOOR' + NH_3 = RCONH_2 + R'OH.$$

Authorities differ as to the effect of alcohol on amid synthesis. One (Bonz, Ph. Ch. 2, 900) says free alcohol must not be present. Another uses alcoholic ammonia in the synthesis. It would seem to us that no general statement should be made, since, in some of our experiments, we easily obtained well-crystallized products, while in others no crystals were obtained; possibly because of the alcohol formed by the reaction.

The method of procedure was similar to that used with chlorids. The ester was dropped into the liquid ammonia contained in a small crystallizing dish insulated by cotton. A large excess of ammonia was used—from six to ten times the bulk of the esters. The dish was covered with a ground-glass plate and allowed to stand until the ammonia was all evaporated. When a crystalline residue was obtained, it was dried on a porous plate and a melting-point determination made. The reaction between the esters and the ammonia is not violent, as when chlorids are used, so that when crystals can be obtained the method is much better than the chlorid method.

Forty-two esters have been treated in this way. From nine of them, crystallized compounds were obtained which had melting-points corresponding to the melting-points given for the respective amids in the literature on the subject. Two gave compounds with higher melting-points, and seven gave products, with high melting-points, that were probably decomposition products. The remainder were apparently not acted upon.

The first esters tried were those of the chloracetic acids. These

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gave such good results that, by analogy, it might have been expected that the method would be general in its application. The yield of amid in each case was quantitative; and they were, moreover, pure and well crystallized, yet, with the exception of cyanacetic ethyl ester, no others have given as good results.

The reaction, too, was much less violent than the one accompanying the formation of the amids from the chlorids. The esters and the ammonia mix with little rise in the temperature of the ammonia.

Cyanacetic ethyl ester gave a well-crystallized body which melted at 118°, agreeing with the melting-point of the substance given by Henry (Bl. 48, 656), but differing from that assigned by Hoff 105° (J. 1864, 561).

The ethyl esters of the fatty acids were tried, as follows: Formic, acetic, propionic, butyric, valeric, caprylic, and pelargonic. None of these yielded amids except pelargonic acid ethyl ester, which gave crystals mixed largely with the unchanged ester. When these crystals were freed from the ester, they gave a melting-point of 99°, agreeing with that given by Hofmann (B. 15, 984).

From the results above described, it seemed probable that the substitution of one or more hydrogen atoms in the alkyl radical of the acid by the halogen had some influence upon the readiness with which an amid could be formed. To test this hypothesis, the action of ammonia on the esters of a number of substituted fatty acids was investigated, with the result that we have thus far obtained amids from only two of them, dibromacetic ethyl ester and chlorpropionic ethyl ester. Substances were obtained from these whose melting-points correspond to those recorded in chemical literature. From some of the others crystalline products were obtained, but the melting-points varied from those recorded for the expected amids. For instance, from the bromacetic ethyl ester a mass of white cubical crystals was formed, which did not melt below 200°, which sublimed at high temperatures, and which turned red on being heated or after standing a a few days. This substance seems to be a mixture of ammonium bromid and some other compound, which we have not yet separated and identified, but which is possibly glycinamid or amidoacetamid. From tribromacetic acid ethyl ester white crystals were obtained which melted at 45° instead of 120°, the temperature at which tribromacetamid should melt (Brezina, J. 1881, 673). The composition of this substance has not yet been determined. Bromin substitution products of esters of some of the higher fatty acids give solid residues resembling that obtained from bromacetic acid ester and probably consisting of ammonium bromid and decomposition products.

The only chlorin substitution product besides the chloracetic

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ethyl esters which was available was chlorpropionic ethyl ester. Thus far the only product obtained from this ester has shown a melting-point of 72°, which is lower than that assigned to chlorpropionamid, (80°), by Beckurts-Otto (B. 9, 1592).

From the foregoing, it appears that the presence of chlorin or cyanogen in the alkyl radical aids in the formation of amids, while the weaker halogen bromin generally causes the compound to break up with the formation of ammonium bromid and decomposition products. We have tried, also, the action of a few esters in which the hydrogen of the alkyl is substituted by an organic radical. These radicals do not seem to aid in amid formation. From phenylacetic ethyl ester we have obtained no results. From benzoylacetic ethyl ester a small amount of a substance was obtained, which melted at 167°. This substance is apparently not identical with the benzoylacetamid of Obriga (A. 266, 232), which melted at 113°.

Acetacetic acid ethyl ester gave a white crystalline substance, which, as the temperature rose to that of the room, quickly liquified, forming a yellow oil. This is undoubtedly the same substance mentioned by Collie (A. 226, 298), who says that at 0° acetacetic acid ethyl ester absorbs dry ammonia gas directly, forming an unstable addition product, $C_6H_{10}O_3NH_3$, which quickly goes over into amidocrotonic acid ethyl ester, $C_6H_{11}NO_2$.

From the esters of dibasic acids, there were available those of oxalic, malonic, succinic and tartaric acids. Two of these only, oxalic and tartaric, gave amids by the above method. The oxamid formed very readily as a white, crystalline powder. It did not melt when heated to 200°, but sublimed at higher temperatures. From tartaric acid ethyl ester, after two treatments with ammonia, a small quantity of a substance, melting at 166°, was obtained. We can find no authority for a melting-point of tartramid.

The action of ammonia on the ethyl esters of lactic, lævulinic and citric acids was also investigated. None of these seemed to be changed by the treatment, except that the citric acid ester became slightly blackened.

Four esters of aromatic acids were tried, ethyl benzoate, methyl benzoate, ethyl phthalate, and ethyl salicylate. Of these the phthalic ester gave a white crystalline compound, which melted at 175°. The melting-point of phthalamid, according to Bülow (A. 236, 188), is 219°.

Four other esters have been treated in this manner. Two of them, orthoformic acid ethyl ester and ethyl carbonate, showed no change, but with ethyl chlorcarbonate a vigorous reaction took place; dense white fumes were formed, and a considerable quantity of an amorphous white substance was left in the vessel. This did not melt

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when heated to 200° but was partly soluble. We have not yet determined whether the substance is ammonium chlorid or whether some of the possible substances have been formed.

ACTION OF ESTERS AT HIGHER TEMPERATURES.

Our failure to obtain some amids by the above method might be due to the low temperature at which the reaction must take place, when the ammonia is boiling under ordinary pressure. Therefore, we attempted to get a more rapid and more complete reaction by heating the mixture of the ester and anhydrous ammonia. The esters were each sealed, with about four times their bulk of liquid ammonia, in strong glass tubes. In one series of experiments these were allowed to warm to the temperature of the room, and in a second series they were heated to 60° or 70°. The tubes were kept sealed for at least twelve hours. They were then cooled with boiling ammonia, opened, the ammonia evaporated off, and the residue examined.

Eight esters, selected as being types of various acids, were treated in this way. Of these, acetic acid ethyl ester gave no definite results. Acetacetic acid ethyl ester formed a mass of crystals which remained for some time after the ammonia was evaporated, but which soon liquified on exposure to the air, forming an oily yellow liquid. We have not yet obtained a satisfactory melting-point for these crystals. Some of the crystals were at once sealed in a glass tube, and have been preserved in this way for more than a year.

Malonic acid ethyl ester formed white crystals of malonamid, identified as such by the melting-point, 170° (Hoff, J. 1875, 528).

Pelargonic acid ethyl ester formed a soapy mass when treated in this way. From this mass, crystals of pelargonic amid were obtained. The result agrees with that from ammonia at its boiling-point under ordinary pressure.

Succinic ethyl ester, benzoic ethyl ester, benzoylacetic ethyl ester and ethyl carbonate gave no results.

In the second series of experiments, in which the tube containing the ester and ammonia was heated to 60° or 70° in a water-bath, six esters were used. Acetic ester gave a product which had the characteristic odor of impure acetamid, but we have not yet succeeded in isolating the pure substance. Tartaric acid ester formed the same white crystalline substance that was formed in the cold.

From benzoic ethyl ester, succinic ethyl ester, valeric ethyl ester and benzoylacetic ethyl ester no results were obtained.

With only one of the esters tried—malonic acid ethyl ester—have we had better results at higher temperatures than with the mixture of ester and ammonia at the boiling-point of the liquid ammonia.

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CONCLUSION.

The few acid chlorids tried, except bromacetylchlorid, gave amids. In our experiments with chlorids and liquid ammonia, we have prepared the amids of the three chloracetic acids and benzamid. Mr. O. F. Stafford has prepared sulfamid.

A few esters, especially the chloracetic ethyl esters, gave better results in forming amids, and the operation was more easily carried out than with the corresponding chlorids. We have, by the addition of esters to liquid ammonia, prepared the amids of the three chloracetic acids, of dibromacetic acid, cyanacetic acid, chlorpropionic acid, pelargonic acid, oxalic acid, and tartaric acid. Malonic acid amid was formed only at a higher temperature.

A few esters gave substances whose melting-points varied from those of expected amids found recorded in chemical literature.

Many of the esters tried have given no well-crystallized amids under the conditions which prevailed in these experiments. The causes for this may be conjectured: First, the low temperature of the reaction, as shown in the case of malonamid, which was not formed at the temperature of boiling ammonia, but which form in a sealed tube at the temperature of the room; second, the short time for the reaction allowed by the evaporation of ammonia from open vessels; third, the reaction of ammonia on esters is reversible, and is even prevented by excess of alcohol (Bonz, Ph. Ch. 8, 900).

We hope to carry our experiments farther, to identify the rest of the substances obtained, and to study the action of liquid ammonia on the esters at higher temperatures and in the presence of diluting media, such as ether and benzene.

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A NEW THEORY OF COLLINEATIONS IN SPACE, II.

BY H. B. NEWSON.

NOTE.—In this journal, Series A, Vol. VI, pp. 63-69, and Vol. IX, pp. 65-71, the writer has enumerated, discussed and constructed the thirteen types of collineations in space; also in volume X, No. 2, the properties of the fundamental group, $G_3(ABCD)$ of type I were discussed. In the present paper the same thing is done for types II, III, and IV. In future papers the remaining types of collineations in space will be treated in the same manner. This series of papers will then be extended to include the synthetic determination and discussion of all real continuous groups of collineations in space and their classification according to the thirteen types.

A knowledge of the corresponding theory in one and two dimensions is assumed on the part of the reader. A memoir on "A New Theory of Collineations in the Plane," though written earlier than the papers of this series, will appear some months hence in the *American Journal of Mathematics*. The memoir treats of all real and imaginary collineations in the plane.

The projected papers, of which the present is the second, are designed to develop completely my theory of real collineations in space. The extension of the theory to include all real and imaginary collineations is so easy that it will readily be made by most readers. The papers will be published in this journal as rapidly as possible.—H. B. N.

A.—*On the Group of Collineations $G_3(ABCl)$ of Type II and its Subgroups.*

THE real collineations in space of type II show two subtypes, viz., hyberbolic and elliptic. In the first subtype the invariant figure is real in all of its parts; in the second subtype the points B and C are conjugate imaginary, and hence the lines AB and AC and the planes ABl and ACl are also conjugate imaginary. These two cases must be treated separately.

§ 1. THE GROUP $hG_3(ABCl)$ AND ITS ONE-PARAMETER SUBGROUPS.

The group $hG_3(ABCl)$.—A collineation T of type II is completely determined by the position of its invariant figure (ABCl) and three parameters k, k′ and t. k is the constant cross-ratio along AB, k′ that along AC, and t is the parabolic constant of the transformation along AC. In the hyperbolic case these three parameters are all real and independent of one another, and hence there are ∞^3 collineations, leaving the figure h(ABCl) invariant; they form a three-parameter group $hG_3(ABCl)$.

THEOREM 1. The aggregate of all collineations of type II having the same invariant figure h(ABCl) forms a three-parameter group $hG_3(ABCl)$.

One-parameter subgroups of $hG_3(ABCl)$.—The group $hG_3(ABCl)$ contains ∞^2 one-parameter subgroups, as we shall now show. Let us

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put $k'=k^{1-r}$, and $k=a^t$; *i. e.*, $k=a^t$ and $k'=a^{(1-r)t}$, where a and r are two real constants. We consider now the system of collineations in $hG_3(ABCl)$ whose parameters satisfy these relations.

Let T and T_1 be two collineations whose parameters are a^t, $a^{(1-r)t}$, t, and a^{t_1}, $a^{(1-r)t_1}$, t_1, respectively. Their resultant, T_2, has the parameters a^{t_2}, $a^{(1-r)t_2}$, t_2 where $t_2=t+t_1$. Since there is only one variable parameter, t, this system contains ∞^1 collineations; these form a one-parameter group, since the resultant of any two collineations of the system is again a collineation of the system. Such a one-parameter group is designated by $hG_1(ABCl)_{ar}$.

There is a one-parameter group within $hG_3(ABCl)$ for each real value of r and each positive value of a; hence $hG_3(ABCl)$ contains ∞^2 one-parameter subgroups. The properties of one of these subgroups are the same as the properties of a one-dimensional parabolic group.

THEOREM 2. The group $hG_3(ABCl)$ contains ∞^2 one-parameter subgroups; for each of these subgroups a and r have fixed values, and t is the variable parameter.

Invariant curves and surfaces of $hG_3(ABCl)_{ar}$.—The one-parameter group $hG_1(ABCl)$ leaves invariant, besides the fundamental figure h(ABCl) a system of ∞^2 path curves and certain systems of surfaces passing through these path curves. We find the equations of these invariant surfaces as follows:

Let (ABCD), where D is some point on l, be the tetrahedron of reference, and let T be a collineation of the group $hG_1(ABCl)$ which transforms a point P whose coordinates are (x, y, z, w) to P_1 whose coordinates are (x_1, y_1, z_1, w_1). Pass planes through PAC and P_1AC. Writing out the cross-ratio of the four planes through AC we have

$$\frac{x_1}{z_1} : \frac{x}{z} = a^t, \tag{1}$$

since this cross-ratio is the same as that along the line AB. In like manner we derive the equations

$$\frac{y_1}{z_1} : \frac{y}{z} = a^{(1-r)t}, \tag{2}$$

$$\frac{y_1}{x_1} : \frac{y}{x} = a^{-rt}, \tag{3}$$

$$\frac{w_1}{z_1} - \frac{w}{z} = t. \tag{4}$$

Suppose that P is a movable point and P_1 fixed, so that any function of the coordinates of P_1 only is a constant. Eliminating t from (1) and (4) we get

$$za^{\frac{w}{z}} = Cx, \qquad \text{I}$$

which is the equation of a family of invariant cones with vertices at

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C. In like manner eliminating t from (2) and (4), (1) and (2), and (3) and (4) we have, respectively,

$$za^{\frac{(1-r)w}{z}} = Cy, \qquad \text{II}$$

$$x^{r-1}\, y = Cz^r, \qquad \text{III}$$

$$ya^{\frac{rw}{z}} = Cx. \qquad \text{IV}$$

Equations I, II, III give families of invariant cones whose vertices are respectively at C, B, and A. Equation IV represents an invariant family of ruled surfaces not conical.

We have thus found four families of ruled surfaces which are invariant under all the collineations of the group $hG_1(ABCl)$. The path curves of the group are the ∞^2 common intersections of these families of surfaces.

THEOREM 3. There are four distinct families of ruled surfaces invariant under all the collineations of the group $hG_1(ABCl)$; three of these are families of cones. The ∞^2 curves of intersection of these invariant surfaces are the path curves of the group.

§ 2. TWO-PARAMETER SUBGROUPS OF $hG_3(ABCl)$.

Two-parameter groups leaving invariant a family of surfaces.— If r remains constant while a assumes in turn all real values between 0 and ∞, and we have ∞^2 one-parameter groups, all of whose transformations leave invariant the family of cones given by equation III, for the equation of this family of cones is independent of a. The path curves of the ∞^1 one-parameter groups all lie on these cones. This system of ∞^2 collineations forms a two-parameter group $hG_2(ABCl)_r$; the parameters of this group are a and t. The group $hG_3(ABCl)$ contains ∞^1 two-parameter subgroups, one for each real value of r.

In like manner if a is constant and r varies, we get a two-parameter group, leaving invariant the family of cones given by equation I. Again, if a and r vary in such a manner that $a^{(1-r)}$ is a constant, we get a two-parameter group leaving invariant the family of cones given by equation II. Finally, if a and r vary so that a^r is constant, we have a two-parameter group whose invariant family of surfaces is given by equation IV.

Thus we see that the group $hG_3(ABCl)$ contains four singly infinite systems of two-parameter subgroups; three of these systems leave invariant families of cones, and one system leaves invariant a family of ruled surfaces.

THEOREM 4. The three-parameter group $hG_3(ABCl)$ contains four singly infinite systems of two-parameter subgroups; these are given by r = const.; a = const.; a^{1-r} = const., and a^r = const.

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§ 3. Some Properties of the Subgroups of $hG_3(ABCl)$.

Negative values of k and k'.—The three parameters of $hG_3(ABCl)$, viz., k, k', t, are all real and each may assume in turn all real values, both positive and negative. Let t, k and k' be taken to be the rectangular coordinates, x, y, z, respectively, of a point in a space S. Evidently there is a collineation in $hG_3(ABCl)$ corresponding to each point in S. The one- and two-parameter groups in $hG_3(ABCl)$ are represented by curves and surfaces in S. The system of curves given by the equations

$$y=a^x \text{ and } z=a^{(1-r)x}, \qquad V$$

in which a and r are parameters, represents the system of one-parameter subgroups of $hG_3(ABCl)$.

In order that the curves given by equations V shall be continuous curves the value of a must be positive. The curve lies always on the positive side of the plane $y=0$ and on the positive side of $z=0$; hence it is confined to the first and second octants. The curves of the family $y=a^x$ and $z=a^{(1-r)x}$ contain every point in the first and second octants but no points in the other six octants. Consequently the group $hG_3(ABCl)$ contains transformations which are not included in any of its subgroups. In fact, only one-third of all the transformations in $hG_3(ABCl)$ are to be found in its subgroups; the transformations for which k and k' are negative cannot be generated from infinitesimal collineations in group $hG_3(ABCl)$.

The curves all pass through the point (0, 1, 1). This point corresponds to the identical transformation which belongs therefore to every one-parameter subgroup of $hG_3(ABCl)$. Every curve of the system is asymptotic to the axis of x, to the right or to the left according as we have $a<1$ or $a>1$.

Theorem 5. Only one-third of the collineations in the group $hG_3(ABCl)$ belong to its one-parameter subgroups and are generated from infinitestimal collineations in $hG_3(ABCl)$.

§ 4. Some Special Subgroups of $hG_3(ABCl)$.

Two-parameter subgroups of types VIII, IX, and XI.—The parameters k, k' and t in $hG_3(ABCl)$ may have such values that the transformation along one or more of the invariant lines of the figure (ABCl) is identical, so that every point on such a line is an invariant point. In such cases the collineations are of another type than II.

If $t=0$ and k and k' vary independently, the one-dimensional transformation along Al is identical, and we have a two-parameter subgroup of type VIII in $hG_3(ABCl)$. If $k'=k$, the one-dimensional transformation along BC is identical, and there results a two-parameter subgroup of type IX in $hG_3(ABCl)$. If $k=1$ or $k'=1$, the

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one-dimensional transformations along AB and AC, respectively, are identical, and there results in each case a two-parameter subgroup of type XI in $hG_3(ABCl)$.

In terms of the parameters a, r and t the subgroup of type VIII results when $a=\infty$; the subgroup of type IX results when $r=0$; the two subgroups of type IX result when $r=1$ and ∞ respectively.

THEOREM 6. The group $hG_3(ABCl)$ contains one two-parameter subgroup of type VIII, one of type IX, and two of type XI.

Subgroups of types VI, VII and X in $hG_3(ABCl)$.—If $t=0$ and $k=1$, the transformation in the plane ABl is identical and leaves invariant all points in the plane. The corresponding collineations in space are of type VI, C being the vertex and ABl the axial plane. The remaining parameter k′ gives us a one-parameter subgroup of type VI in $hG_3(ABCl)$. In like manner, if $t=0$ and $k'=1$, we have a one-parameter subgroup of type VI whose vertex is B and whose axial plane is ACl.

If $k=1$ and $k'=1$, the collineation in the plane ABC is identical, the parameter t gives us a one-parameter subgroup of type VII in $hG_3(ABCl)$; A being the vertex and ABC the axial plane.

If $t=0$ and $k'=k$, the one-dimensional transformations along AC and BC are both identical; there results a one-parameter subgroup of type X in $hG_3(ABCl)$.

In terms of a, r and t the subgroup of type VII is given by $a=1$; the two subgroups of type VI are given by $t=0$ and $r=1$, $t=0$ and $r=\infty$, respectively; the subgroup of type X is given by $t=0$ and $r=0$.

THEOREM 7. The group $hG_3(ABCl)$ contains one one-parameter subgroup of type VII, two of type VI, and one of type X.

Other special subgroups of $hG_3(ABCl)$.—There are only three other special subgroups of $hG_3(ABCl)$ to be noticed; these are when the path curves in the plane ABC are conics. These path curves are conics for three values of r, viz., $r=-1$, 2, 1/2. When $r=2$ the conics have double contact at B and C; when $r=-1$ or 1/2 the conics have double contact at A and C, A and B, respectively. These are two-parameter subgroups of $hG_3(ABCl)$.

§ 5. THE ELLIPTIC CASE $eG_3(ABCl)$.

Parameters of $eG_3(ABCl)$.—In the elliptic subtype of type II, where the points B and C are conjugate imaginary, the theory is somewhat different from that of the hyperbolic subtype. In the plane ABC the two-dimensional collineations of the elliptic subtype and the parameters are given in the form $k=\exp.(c+i)\theta$; thus c and θ are the parameters. The three parameters of eG_3 are there-

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fore c, θ, and t. It is convenient to replace θ by nt and thus have c, n, t as the three parameters.

Let T and T_1 be any two collineations of the group $eG_3(ABCl)$ for which the parameters are c, n, t and c_1, n_1, t_1, respectively. Let the values of the parameters of the resultant be c_2, n_2, t_2. We have, therefore, $t_2 = t + t_1$, $n_2 t_2 = nt + n_1 t_1$, and $c_2 n_2 t_2 = cnt + c_1 n_1 t_1$.

One- and two-parameter subgroups of $eG_3(ABCl)$.—If c and n remain constant and only t varies, we get a one-parameter subgroup of eG_3. If c is fixed and n and t vary, or n fixed and c and t vary, there result two-parameter subgroups. Thus we have two distinct singly infinite systems of two-parameter subgroups and ∞^2 one-parameter subgroup of $eG_3(ABCl)$. The path curves of the one-parameter subgroup are, except in very special cases, transcendental curves; in these special cases the subgroups are of other types than type II.

Special subgroups of $eG_3(ABCl)$.—If $t=0$ and c and θ vary, the transformation along the line Al is identical and there remains a two-parameter elliptic subgroup of type VIII. When $c=\infty$, $n=0$, $cn \pm 0$, the transformation along BC is identical, and there results a two-parameter subgroup of type IX. When $c=\infty$, $n=0$, and $cn=0$, the transformation in the plane ABC is identical, and there results a one-parameter subgroup of type VII. When $t=0$, $c=\infty$, $n=0$, and $cn=0$, *i. e.*, when the conditions for a two-parameter group of type VIII and type IX are simultaneously fulfilled, the transformations along both Al and BC are identical, and there results a one-parameter subgroup of type X. The elliptic group $eG_3(ABCl)$ has no real subgroups of types VI or XI.

THEOREM 8. The group $eG_3(ABCl)$ contains one two-parameter group of type VIII and one of type IX; also one one-parameter subgroup of type VII and one of type X.

The group $eG_3(ABCl)$ contains one other two-parameter subgroup worthy of special notice. When $c=0$ the path curves of the one-parameter group of collineations in the plane ABC are conics having double contact at B and C. This group derives its importance from the fact that, in case the plane ABC is at infinity and the points B and C are the circular points in the plane, it becomes the group of all screw motions about the line l as an axis.

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B.—*On the Group of Collineations $G_3(ABll')$ of Type III and its Subgroups.*

§1. The Group $G_3(ABll')$ and its One-parameter Subgroup.

The group $G_3(ABll')$.—A real collineation in space of type III leaves invariant a figure (ABll') real in all of its parts, consisting of two points A and B and their join; two lines l and l', the first through A and the second through B; and hence also the two planes ABl and ABl'. The one-dimensional transformations along l and l' are both parabolic; that along AB hyperbolic. The plane collineations in the invariant planes ABl and ABl' are both of type II.

A collineation T of type III is completely determined by the position of its invariant figure (ABll') and three parameters k, t, t'; k is the constant cross-ratio along AB, t is the parabolic parameter along Al, and t' that along Bl'. These three parameters are all real and vary independently; hence there are ∞^3 collineations of type III, leaving the fundamental figure (ABll') invariant; these form a three-parameter group $G_3(ABll')$.

Theorem 9. The aggregate of all collineations of type III in space having the same invariant figure (ABl'l) forms a three-parameter group $G_3(ABll')$.

One-parameter subgroups of $G_3(ABll')$.—It will now be shown that the group $G_3(ABll')$ contains ∞^2 one-parameter subgroups. Let $k=a^t$ and $t'=nt$, where a and n are constants; a is necessarily positive. By imposing these conditions on the parameters k and t', we select from $G_3(ABll')$ a system of ∞^1 collineations. The properties of this system are now to be examined.

Let T and T_1 be two collineations whose parameters are respectively a^t, nt, t, and a^{t_1}, nt_1, t_1. Their resultant, T_2, has the parameters a^{t_2}, n_2t_2, t_2. For along Al we have $t_2=t+t_1$; along Bl' we have $n_2t_2=nt+n_1t_1$; along AB we have $k_2=kk_1=a^t$. $a^{t_1}=a^{t+t_1}$. Hence the system of ∞^1 collineations, whose parameters are a^t, nt, t, forms a one-parameter continuous group whose parameter is t. This group is designated by $G_1(ABll')_{an}$.

There is a one parameter subgroup within $G_3(ABll')$ for each value of n and each positive value of a; hence $G_3(ABll')$ contains ∞^2 one-parameter subgroups. The properties of one of these subgroups are the same as the properties of a one-dimensional parabolic group.

Theorem 10. The group $G_3(ABll')$ contains ∞^2 one-parameter subgroups; for each of these subgroups a and n have fixed values and t is the variable parameter.

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Invariant curves and surfaces of $G_1(ABll')$.—We shall now determine the systems of invariant surfaces of the one-parameter group $G_1(ABll')$, whose intersections are the ∞^2 path curves of the group. Let (ABCD), where C is some point on l' and D some point on l, be the tetrahedron of reference; and let T be a collineation of the group $G_1(ABll')$ which transforms a point P, whose coordinates are (x, y, z, w) to P_1 whose coordinates are (x_1, y_1, z_1, w_1). Pass planes through PAl, P_1Al, PAl', P_1Al', PAB, and P_1AB. We obtain at once the following equations:

$$\frac{x_1}{y_1} - \frac{x}{y} = t' = nt, \tag{1}$$

$$\frac{w_1}{z_1} - \frac{w}{z} = t, \tag{2}$$

$$\frac{y_1}{z_1} : \frac{y}{z} = a^t. \tag{3}$$

By eliminating t from these equations of transformation we obtain the following equations of invariant surfaces of $G_1(ABll')$:

$$y = Ca^{\frac{w}{z}}z, \qquad \text{I}$$

$$y = Ca^{\frac{t}{nz}}z, \qquad \text{II}$$

$$(x - cy)z = nwy. \qquad \text{III}$$

Equations I and II represent families of transcendental ruled surfaces while equation III always represents a family of quadric surfaces. The intersections of these three systems of surfaces are the path curves of the group $G_1(ABll')$.

THEOREM 11. There are three distinct families of ruled surfaces invariant under all the collineations of the group $G_1(ABll')$; two of these families are transcendental surfaces and one is a family of quadrics. These surfaces intersect in the path curves of the group.

§ 2. TWO-PARAMETER SUBGROUPS OF $G_3(ABll')$.

Subgroups with transcendental invariant surfaces.—Let a, n and t be the three parameters of $G_3(ABll')$. If a remains constant while n and t vary, we have a one-parameter subgroup all of whose transformations leave invariant the family of transcendental surfaces given by equation I. These form a two-parameter group, and there is one such group for each positive value of a.

If a and n vary in such a manner that a^n remains constant and t varies independently, we get a two-parameter subgroup of $G_3(ABll')$, leaving invariant the family of surfaces given by equation II. There is one such subgroup for each value of the constant a^n.

Subgroups with invariant quadric surfaces.—If n remains constant and k and t vary independently, we have a two-parameter sub-

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group, leaving invariant the family of quadric surfaces given by equation III. There is one such subgroup for each value of n.

The lines l and l′ are two generators of the same system and AB a generator of the other system on every invariant quadric. These invariant quadrics always have both systems of generators real.

THEOREM 12. The three-parameter group $G_3(ABll')$ contains three singly infinite systems of two-parameter subgroups. These are given by $a=\text{const.}$; $a^n=\text{const.}$; and $n=\text{const.}$ Every collineation of type III leaves invariant a family of quadric surfaces.

§ 3. SOME PROPERTIES OF THE SUBGROUP OF $G_3(ABll')$.

Graphic representation of subgroups of $G_3(ABll')$.—The three parameters t, t′, k of $G_3(ABll')$ are all real and may be taken as the coordinates x, y, z, respectively, of a point in a space S. There is a collineation of the group for each real point in S. The one- and two-parameter subgroups of $G_3(ABll')$ are represented by curves and surfaces respectively in S.

The surfaces given by the equations

$$z=a^x \text{ and } y=nx$$

represent the two-parameter subgroups, and their curves of intersection represent graphically the one-parameter subgroups of $G_3(ABll')$.

These curves representing the one-parameter subgroups lie entirely in the space above the plane $z=0$. No collineation in $G_3(ABll')$ with negative value of k belongs to one of its one-parameter subgroups. Consequently one-half of the collineations of the group cannot be generated from infinitesimal collineations of the group.

The point (0, 0, 1) is on every curve of the system representing the subgroups; hence the identical collineation is common to every one-parameter subgroup of $G_3(ABll')$. Other properties of these groups are easily deduced from the properties of this family of curves.

THEOREM 13. Only one-half of the collineations in $G_3(ABll')$ belong to its one-parameter subgroups and can be generated from the infinitesimal collineations in $G_8(ABll')$.

§ 4. SOME SPECIAL SUBGROUPS OF $G_3(ABll')$.

Two-parameter subgroups of types IX and XII.—The invariant figure of a collineation of type III has three invariant lines, Al, Bl′, and AB. If t or t′ is zero, the one-dimensional transformation along Al or Bl′, respectively, is identical, and the resulting collineation is of type IX. If k and one of the t's vary while the other t is zero, we have a two-parameter subgroup of $G_3(ABll')$. Thus $G_3(ABll')$ contains two two-parameter subgroups of type IX.

If $k=1$, the one-dimensional transformation along AB is identical

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and all points on the line are invariant; thus a transformation of this kind is of type XII. If t and t' vary while k=1, we have ∞^2 collineation of type XII, all having the same invariant figure and forming a two-parameter subgroup of $G_3(ABll')$.

THEOREM 14. The group $G_3(ABll')$ contains two two-parameter subgroups of type IX and one of type XII.

One-parameter subgroups of types VII and X.—If t=0 and k=1, the collineations in the plane ABl are identical, and the resulting collineations in space are of type VII and form a one-parameter subgroup. In like manner, if t'=0 and k=1, we have another one-parameter subgroup of type VII, ABl' being the axial plane and B the vertex of its invariant figure. Thus $G_3(ABll')$ contains two subgroups of type VII.

If t=0 and t'=0 while k varies, the resulting ∞^1 collineations are of type X and form a one-parameter subgroup of this type. Al and Bl' are the two axes of the skew perspective collineation and k is the parameter.

THEOREM 15. The group $G_3(ABll')$ contains two one-parameter subgroups of type VII and one of type X.

C.—*On the Group of Collineations $G_4(ABlp)$ of Type IV and its Subgroups.*

§ 1. THE GROUP $G_4(ABlp)$ AND ITS SUBGROUPS.

The group $G_4(ABlp)$.—A real collineation in space of type IV leaves invariant a figure (ABlp) real in all of its parts, consisting of two planes p and p' intersecting in a line l, two points A and B and their join l' in the plane p, A being on l. The one-dimensional transformations along l and l' are parabolic and hyperbolic, respectively. The two-dimensional transformations in the planes p and p' are of types III and II, respectively.

A collineation T of type IV is completely determined by its invariant figure (ABlp) and four parameters k, t, n, h; k is the constant cross-ratio along AB, and t, n, h are the three parameters of group of plane collineations of type III in the plane p. These four parameters are all real and may vary simultaneously, thus giving ∞^4 collineations, all having the same invariant figure. These form a four-parameter group $G_4(ABlp)$.

THEOREM 16. The aggregate of all collineations of type IV having the same invariant figure (ABlp) forms a four-parameter group $G_4(ABlp)$.

One-parameter subgroups of $G_4(ABlp)$.—The group contains

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∞^3 one-parameter subgroups. To show this, let $k=a^t$ and let a, n and h be constants. There are ∞^1 collineations in the group $G_4(ABlp)$ which satisfy these conditions. In the plane p the plane collineations form a one-parameter group of type III, and in the plane ABl they form a one-parameter group of type II. t is the single independent variable parameter. These ∞^1 collineations in space evidently form a one-parameter group. There are ∞^3 such groups in $G_4(ABlp)$, one for each positive value of a and each real value of n and h. Such a one-parameter group is designated by $G_1(ABlp)anh$. The properties of the group $G_1(ABlp)anh$ are those of a one-parameter parabolic group in one dimension.

THEOREM 17. The group $G_4(ABlp)$ contains ∞^3 one-parameter subgroups $G_1(ABlp)anh$; for each subgroup a, n and h are constants and t is the variable parameter.

Invariant curves and surfaces of $G_1(ABlp)anh$.—The systems of invariant surfaces whose intersections are the path curves of the group $G_1(ABlp)anh$ are determined as follows: Let (ABCD), where C is on l and D in the plane p, be the tetrahedron of reference, and let T be a collineation of the group $G_1(ABlp)$ which transforms the point $P=(x, y, z, w)$ to $P_1=(x_1, y_1, z_1, w_1)$. From the properties of the invariant figure we easily obtain the following equations of transformation:

$$\frac{x_1}{y_1} : \frac{x}{y} = a^t, \tag{1}$$

$$\frac{y_1}{z_1} - \frac{y}{z} = t, \tag{2}$$

$$\frac{w_1}{z_1} = \frac{w}{z} + nt\frac{y}{z} + \frac{n}{2}t^2 + ht. \tag{3}$$

By eliminating t from these equations taken two and two we obtain the following:

$$x = Ca^{\frac{y}{z}}z, \qquad \text{I}$$

$$\frac{w}{z} - n\frac{\log\frac{x}{z}}{\log a}\frac{y}{z} + \frac{w}{2}\frac{\log^2\frac{x}{z}}{\log^2 a} - h\frac{\log\frac{x}{z}}{\log a} = C, \qquad \text{II}$$

$$\frac{n}{2}y^2 + hyz - wz = Cz^2. \qquad \text{III}$$

These equations represent the invariant families of surfaces whose intersections are the path curves of the group. Equation III is a system of quadric cones with vertices at B and the line AB as a common element.

THEOREM 18. There are three distinct families of ruled surfaces invariant under all the collineations of the group $G_1(ABlp)anh$. Two of these families are transcendental surfaces and one is a family of quadric cones.

Two- and three-parameter subgroups of $G_4(ABlp)$.—If a is con-

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stant and n, h, t variable, we have a three-parameter subgroup of $G_4(ABlp)$. All collineations of this group $G_3(ABlp)$ leave invariant the family of surfaces given by l. If n is constant while a, h and t vary, we have another three-parameter group $G_3(ABlp)n$. This group leaves invariant a system of ∞^2 quadric cones. There are thus two systems of three-parameter subgroups of $G_4(ABlp)$, one for each positive value of a and one for each real value of n.

If a and n are both constant while h and t vary, we have a two-parameter subgroup of $G_4(ABlp)$. If h and n are both constant and k and t vary, we have another two-parameter group. The invariant surfaces are easily determined. Thus there are two systems of two-parameter subgroups of $G_4(ABlp)$.

THEOREM 19. The group $G_4(ABlp)$ contains two singly infinite systems of three-parameter subgroups and two doubly infinite systems of two-parameter subgroups.

Since k is both positive and negative, and since only these collineations with positive k can be generated from infinitesimal transformations of the group, it follows that only one-half of the collineations in the group $G_4(ABlp)$ belong to its one-parameter subgroups.

§ 2. SOME SPECIAL SUBGROUPS OF $G_4(ABlp)$.

Three-parameter subgroups of type XIII.—When $k=1$, or, what amounts to the same thing, when $a=1$, the one-dimensional transformation along the line AB is identical, and hence every point on the line is an invariant point; dualistically every plane through the line l is an invariant plane. Therefore, the resulting transformations are of type XIII. Since there are three remaining parameters, n, h, and t, we have a three-parameter subgroup of type XIII.

Three-parameter subgroup of type XI.—If $n=0$, the three-parameter group of type III in the plane p reduces to a two-parameter group of type V. The resulting collineations in space are of type XI, since every point on l is invariant, and form a three-parameter group whose parameters are k, h, and t. Also, if we put $t=0$, $nt \pm 0$, and $ht \pm 0$, the ∞^2 collineations in the plane p are again of type V and form a two-parameter group. Thus we have another three-parameter group of type XI.

Two-parameter subgroup of type VII.—If $a=1$ and $n=0$, all points in the plane ABl are invariant and the collineations are of type VII. They form a two-parameter group of type VII. Also, if $a=1$ and $t=0$, but $nt \pm 0$ and $ht \pm 0$, we have left a two-parameter group of type VII, dualistic to the last.

THEOREM 20. The group $G_4(ABlp)$ contains one three-parameter subgroup of type XIII, two three-parameter subgroups of type XI, and two two-parameter subgroups of type VII.

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A NEW THEORY OF COLLINEATIONS IN SPACE, III.

Collineations of Type V in Space.

BY H. B. NEWSON.

A.—*Synthetic Forecast.*

Invariant figure of T.—The fundamental invariant figure of a collineation in space of type V consists* of a plane p, a line l, and a point A; A and l are both in p and A is on l. Let this invariant figure be denoted by (Apl), and let T be a collineation of type V, leaving (Apl) invariant. The collineation T and its invariant figure (Apl) are both self-dualistic. Along the line l and in the pencil of planes through l, T produces a one-dimensional parabolic transformation; in the plane p and in the bundle of rays through A, T produces two-dimensional transformations of type III.

The group $G_6(Apl)$.—The two-dimensional transformations of type III in p, leaving the lineal element Al invariant, are ∞^3 in number and form a three-parameter group with one- and two-parameter subgroups. This three-parameter group leaves invariant the system of ∞^3 conics touching l at A; a two-parameter subgroup leaves invariant a net of ∞^2 of these conics having three points in common at A; a one-parameter subgroup leaves invariant each of a pencil of ∞^1 conics having four points in common at A.

Dualistically the two-dimensional transformations of type III in the bundle of rays through A are ∞^3 in number, and form a three-parameter group with one- and two-parameter subgroups, leaving invariant the system of ∞^3 quadric cones having their vertices at A and touching p along the line l; a two-parameter subgroup leaves invariant a net of ∞^2 of these cones having three elements in common along l; a one-parameter subgroup leaves invariant each of a pencil of ∞^1 cones having four elements in common along A.

These two two-dimensional three-parameter groups are independent of each other, and hence the three-dimensional transformations of type V, leaving (Apl) invariant, depend upon six parameters; *i. e.*, they are ∞^6 in number, and form a six-parameter group $G_6(Apl)$.

THEOREM 1. There are ∞^6 collineations of type V in space leaving the figure (Apl) invariant; these form a six-parameter group $G_6(Apl)$.

* Kansas University Quarterly, Vol. IX, p. 70.

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Subgroups of $G_6(Apl)$.—There are two varieties of five-parameter subgroups of $G_6(Apl)$. One of these subgroups consists of all collineations in $G_6(Apl)$ which leave invariant a net of ∞^2 conics in p and the system of ∞^3 cones through A. A subgroup of the other variety consists of all collineations in $G_6(Apl)$ which leave invariant the system of ∞^3 conics in p and a net of ∞^2 cones through A. These two varieties of five-parameter groups form a dualistic pair. There are ∞^1 groups of each variety.

There are three varieties of four-parameter subgroups in $G_6(Apl)$, viz.: (1) All those collineations in $G_6(Apl)$, which leave invariant a net of ∞^2 conics in p and a net of ∞^2 cones through A, form a subgroup; (2) all those collineations, which leave invariant a pencil of ∞^1 conics in p and all cones through A, form a subgroup; (3) all collineations in $G_6(Apl)$, which leave invariant the ∞^3 conics in p and a pencil of ∞^1 cones through A, form a subgroup. The second and third varieties form a dualistic pair and the first is self-dualistic.

There are two varieties of three-parameter subgroups in $G_6(Apl)$, viz.: (1) All collineations in $G_6(Apl)$, which leave invariant a net of ∞^2 conics in p and a pencil of ∞^1 cones through A, form a subgroup; (2) all collineations in $G_6(Apl)$, which leave invariant a pencil of ∞^1 conics in p and a pencil of ∞^2 cones through A, form a subgroup. These two group varieties form a dualistic pair.

There are ∞^4 two-parameter subgroups of $G_6(Apl)$. One of these subgroups consists of all collineations which leave invariant a pencil of conics in p and a pencil of cones through A. There is only one variety of such two-parameter groups.

In the above two-parameter group the parameters of the two-dimensional transformations in p and through A are t and t', respectively. If we set $t'=gt$ and keep g constant, we obtain a one-parameter subgroup of $G_6(Apl)$.

THEOREM 2. There are nine varieties of subgroups of type V in the group $G_6(Apl)$, viz.: Two varieties of five-parameter subgroups, three of four-parameter subgroups, two of three-parameter subgroups, one of two-parameter subgroups, and one of one-parameter subgroups.

Special subgroups of $G_6(Apl)$.—The group $G_6(Apl)$ contains a number of subgroups composed of collineations of lower types than type V, viz., groups of type XIII, XII, and VII. The three-parameter group of type III in the plane p contains two two-parameter subgroups of elations, viz., $H'_2(A)$ and $H'_2(l)$. The collineations in $G_6(Apl)$, whose plane collineations in p are of type V, are generally of type XIII. Hence, corresponding to the two groups $H'_2(A)$ and $H'_2(l)$ in p, the group $G_6(Apl)$ contains two five-parameter subgroups of type XIII. These five-parameter groups contains four- and three-

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parameter subgroups of type XIII; but these details belong more properly to the theory of type XIII, and will be discussed under that heading.

If the transformation in the plane p is identical, the collineations are of type VII, and form a three-parameter group $G_3(p)$. Dualistically, if the two-dimensional transformation through A is identical, the collineations are of type VII in space and form a three-parameter group of type VII, $G_3(A)$. Thus $G_6(Apl)$ contains a dualistic pair of three-parameter subgroups of type VII.

If the one-dimensional transformations along the line l and in the pencil of planes through l are both identical, the collineations are of type XII. Of the ∞^6 collineations in $G_6(Apl)$, ∞^4 satisfy these two conditions, and hence this group contains ∞^4 collineations of type XII. These constitute a four-parameter group of type XII. The constitution of this group will be discussed in the proper place in this series of papers.

THEOREM 3. The group $G_6(Apl)$ contains two five-parameter subgroups of type XIII, two three-parameter subgroups of type VII, and one four-parameter subgroup of type XII.

B.—*Analytic Verification.*

§ 1. THE SIX-PARAMETER GROUP $G_6(Apl)$.

Analytic expression for T.—Along the line l and in the pencil of planes through l the collineation T produces one-dimensional parabolic transformations whose constants we shall designate by mt and nt, respectively. Let h, k and g be three other constants determining T. Let the tetrahedron of reference (ABCD) be taken so that B is on l, C in the plane p, and D anywhere in space. The plane p is now the plane $z=0$; $y=0$ passes through l; $x=0$ passes through A; and $w=0$ is not specially related to the invariant figure. The collineation T is expressed by the following equations:

$$\frac{y_1}{z_1} = \frac{y}{z} + nt, \tag{1}$$

$$\frac{x_1}{z_1} = \frac{x}{z} + t\frac{y}{z} + \frac{n}{2}t^2 + ht, \tag{2}$$

$$\frac{w_1}{z_1} = \frac{w}{z} + mt\frac{x}{z} + \left(\frac{m}{2}t^2 + ht\right)\frac{y}{z} + \frac{mn}{6}t^3 + \left(\frac{hm+kn}{2}\right)t^2 + gt. \tag{3}$$

These equations may be thrown into the form:

$$\frac{x_1}{w_1} = \frac{x + ty + \left(\frac{n}{2}t^2 + ht\right)z,}{w + mtx + \left(\frac{m}{2}t^2 + kt\right)y + \left(\frac{mn}{6}t^3 + \frac{(hm+kn)}{2}t^2 + gt\right)z,} \tag{4}$$

$$\frac{y_1}{w_1} = \frac{y + tz,}{w + mtx + \left(\frac{m}{2}t^2 + kt\right)y + \left(\frac{mn}{6}t^3 + \frac{(hm+kn)}{2}t^2 + gt\right)z,} \tag{5}$$

$$\frac{z_1}{w_1} = \frac{z}{w + mtx + \left(\frac{m}{2}t^2 + kt\right)y + \left(\frac{mn}{6}t^3 + \frac{(hm+kn)}{2}t^2 + gt\right)z.} \tag{6}$$

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That T is correctly expressed by these equations is shown as follows: (1) shows that the one-dimensional transformation in the pencil of planes through l is parabolic; (1) and (2) show that the two-dimensional transformation in the bundle of rays through A is of type III; (4), (5) and (6) show that A = (0, 0, 0, w) is an invariant point; (6) shows that z = 0 is an invariant plane; making z = 0 in (4), (5), and (6), the modified form of (4) and (5) shows that, in the plane p, l is an invariant line and that the collineation in p is of type III.

Six-parameter group $G_6(Apl)$.—The numbers m, n, h, k, g, t may vary independently, and hence there are ∞^6 collineations of type V, each leaving (Apl) invariant. Let T_1 be a second collineation of the same system, whose constants are m_1, n_1, h_1, k_1, g_1, t_1, and which transforms P_1 to P_2. Eliminating x_1, y_1, z_1, w_1 from T and T_1, we get T_2, whose equations are of the same form as those of T and whose constants are m_2, n_2, h_2, k_2, g_2, t_2. We find the following values of t_2, etc.:

$$t + t_1 = t_2, \tag{7}$$

$$nt + n_1t_1 = n_2t_2, \tag{8}$$

$$mt + m_1t_1 = m_2t_2, \tag{9}$$

$$\frac{nt^2 + 2ntt_1 + n_1t_1^2}{2} + ht + h_1t_1 = \frac{n_2}{2}t_2^2 + h_2t_2, \tag{10}$$

$$\frac{mt^2 + 2m_1tt_1 + m_1t_1^2}{2} + kt + k_1t_1 = \frac{m_2}{2}t_2^2 + k_2t_2, \tag{11}$$

$$\frac{mnt^3 + 3m_1nt^2t_1 + 3m_1ntt_1^2 + m_1n_1t_1^3}{6} + \frac{(hm + kn)t^2 + 2(hm_1 + k_1n)tt_1 + (h_1m_1 + k_1n_1)t^2}{2} +$$

$$gt + g_1t_1 = \frac{m_2n_2}{6}t_2^3 + \frac{h_2m_2 + k_2n_2}{2}t_2^2 + g_2t_2. \tag{12}$$

These six equations show that all the parameters are essential, and that we have a six-parameter group; thus verifying theorem 1.

§ 2. One-parameter Subgroups of $G_6(Apl)$.

The one-parameter group $G_1(Apl)$.—If we keep m, n, h, k and g fixed and let t alone vary, we select thus from $G_6(Apl)$ ∞^1 collineations which form a one-parameter subgroup of $G_6(Apl)$. This follows from the fact that under these conditions there are no longer six independent equations (7)–(12), but only one, viz., (7). The parameter of the group is t, and the equation $t + t_1 = t_2$ tells us that its properties are those of a one-dimensional parabolic group. Evidently there are ∞^5 such subgroups of $G_6(Apl)$, one for each value of m, n, h, k, g. Such a group is designated by $G_1(Apl)$. This is the only variety of one-parameter subgroups contained in $G_6(Apl)$; for if any other parameter besides t be made to vary alone and the other five be kept fixed, the resulting ∞^5 collineations do not form a group. Equations (7)–(12) confirm this statement.

Invariant curves and surfaces of $G_1(Apl)$.—The families of sur-

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faces invariant under the collineations of the group $G_1(Apl)$ are obtained by eliminating t from all pairs of equations formed from (1), (2), and (3). From (1) and (2) we get:

$$f(x_1, y_1, z_1) \equiv f(z, y, z) \equiv \tfrac{1}{2}y^2 + hyz - nxz - Cz^2 = 0. \qquad I$$

From (1) and (3), and making use of the identity in I, we get:

$$f(x_1, y_1, z_1, w_1) \equiv f(z, y, z, w) \equiv \tfrac{m}{3}y^3 + \tfrac{hm-kn}{2}y^2z - mnxyz - gnyz^2 + n^2wz^2 - Cz^3 = 0. \qquad II$$

From (2) and (3), and using the identities in I and II, we get:

$$f(x_1, y_1, z_1, w_1) \equiv f(x, y, z, w) \equiv \left\{ x\left[\tfrac{m}{6}(hz + y) + \tfrac{kn}{2}z\right] - \tfrac{nwz}{2} \right\}^2 + \left\{ x(gz + ky + \tfrac{2mx}{3}) - w(hz + y) \right\} \left\{ \tfrac{nz}{2}(gz + ky + \tfrac{2mx}{3}) - (hz + y)\left[\tfrac{m}{6}(hz + y) + \tfrac{kn}{2}z\right] \right\} - Cz^4 = 0. \qquad III$$

Making $z = 0$ in equations (4), (5), and (6), the last disappears, and the modified forms of (4) and (5) can be put into the form:

$$\begin{cases} \frac{x_1}{y_1} = \frac{x}{y} + t \\ \frac{w_1}{y_1} = \frac{w}{y} + mt\frac{x}{y} + \frac{m}{2}t^2 + kt. \end{cases} \qquad (10)$$

Eliminating t from these, we have the following equation of the invariant conics in the plane p:

$$f(x_1, y_1, w_1) \equiv f(x, y, w) \equiv \tfrac{m}{2}x^2 + kxy - yw = Cy^2. \qquad IV$$

In I, II, III, and IV, C is the arbitrary parameter of the family of surfaces.

Equation I represents a system of quadric cones having A for a common vertex, l for a common element, and p for a common tangent plane. Equation II represents a family of cubic ruled surfaces having l for a common line and the plane p for an inflectional tangent plane along the line l. The curves of intersection of I and II are the path curves of the group $G_1(Apl)$.

The two families of surfaces have the line l in common; hence their curves of intersection are of a lower degree than the sixth. Taking a section of both surfaces by the plane $w = 0$, we get the following system of curves:

$$\tfrac{1}{2}y^2 + hyz - nxz = Cz^2 \text{ and } \tfrac{m}{3}y^3 + \tfrac{hm-kn}{2}y^2z - mnxyz - gnyz^2 = Cz^3. \qquad (11)$$

Eliminating x from these equations, we find three points of intersection exclusive of those on l. Hence the intersections of the systems of surfaces I and II are ∞^2 twisted cubics in space. They all pass through A and have l for a common tangent at A.

THEOREM 4. The group $G_6(Apl)$ contains ∞^5 one-parameter sub-

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groups; the path curves of one of these subgroups are twisted cubics; each subgroup leaves invariant a family of quadric cones, a family of cubic cones, and a family of quartic surfaces.

§ 3. Other Subgroups of $G_6(Apl)$.

Five-parameter subgroups of $G_6(Apl)$.—If m be kept fixed and the other five parameters be allowed to vary, the resulting collineations form a five-parameter group $G_6(Apl)m$. If we make $m_1 = m$ a constant in equations (7)-(12), we find also $m_2 = m$, and equation (9) is no longer independent. The remaining five equations show the five-parameter group. There are ∞^1 such subgroups in $G_6(Apl)$, one for each real value of m. The group $G_5(Apl)m$ leaves invariant a net of ∞^2 conics in the plane p.

In exactly the same way it may be shown that when $n_1 = n$ also $n_2 = n$, and we have another singly infinite system of five-parameter subgroups $G_5(Apl)n$. The group $G_5(Apl)n$ leaves invariant a net of ∞^2 quadric cones with their vertices at A.

Four-parameter subgroups of $G_6(Apl)$.—If n and h are both constant while the other four parameters vary, the remaining ∞^4 collineations form a four-parameter subgroup of $G_6(Apl)$. This is shown by the vanishing of equations (8) and (10); the remaining four show a four-parameter subgroup. There is a doubly infinite system of these four-parameter groups, one for each value of n and h. One of these groups, $G_4(Apl)nh$, leaves invariant a singly infinite system of quadric cones contained in I.

If m and k are both constant while the other four parameters vary, the remaining ∞^4 collineations form a four-parameter group $G_4(Apl)mk$. This is shown by the vanishing of equations (9) and (11); the remaining four equations show the four-parameter group. There is a doubly infinite system of these four-parameter subgroups, one for each value of m and k. The group $G_4(Apl)mk$ leaves invariant a pencil of conics in the plane p.

If m and n are both constant while h, k, g, t vary independently, we have another four-parameter subgroup of $G_6(Apl)$. The six equations (7)-(12) reduce to

$$t + t_1 = t_2,\ ht + h_1t_1 = h_2t_2,\ kt + k_1t_1 = k_2t_2, \text{ and}$$

$$\frac{(hm + kn)t^2 + 2(h_1m + k_1n)tt_1 + (h_1m + k_1n)t^2}{2} + gt + g_1t_1 = \frac{h_2m + k_2n}{2}t_2^2 + g_2t_2.$$

The group $G_4(Apl)mn$ leaves invariant a net of ∞^2 conics in p and a net of ∞^2 cones through A. There is a doubly infinite system of these four-parameter subgroups, one for each value of m and n.

Three-parameter subgroups of $G_6(Apl)$.—There are two triply infinite systems of three-parameter subgroups of $G_6(Apl)$; one of these

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results when m, n and h are constant, the other when m, n and k are constant. In the first case the group $G_3(Apl)mnh$ leaves invariant a net of conics in p and a pencil of cones through A; in the second case the group $G_3(Apl)mnk$ leaves invariant a pencil of conics in p and a net of cones through A.

Two-parameter subgroup of $G_6(Apl)$.—When m, n, h, k are all constant and g and t alone vary, the ∞^2 collineations form a two-parameter subgroup of $G_6(Apl)$. Evidently there is a quadruply infinite system of these two-parameter groups. The group $G_2(Apl)mnhk$ leaves invariant a pencil of conics in p and a pencil of cones through A.

THEOREM 6. The group $G_6(Apl)$ contains two singly infinite systems of five-parameter subgroups, three doubly infinite systems of four-parameter subgroups, two triply infinite systems of three-parameter subgroups, and one quadruply infinite system of two-parameter subgroups. These are characterized by $m=c$; $n=c$; $m=c$ and $n=c$; $n=c$ and $h=c$; $m=c$ and $k=c$; $m=c$, $n=c$, $h=c$; $m=c$, $n=c$, $k=c$; $m=c$, $n=c$, $h=c$, $k=c$.

§ 3. SOME SPECIAL SUBGROUPS OF $G_6(Apl)$.

Groups of type XIII in $G_6(Apl)$.—For any constant value of m we have a five-parameter subgroup of $G_6(Apl)$; for the special value $m=0$ the subgroup requires special attention. Let $m=0$ in equation IV; it reduces to $y(kx-w-Cy)=0$, *i. e.*, the conics in p break up into the invariant line $y=0$ and the pencil of lines $kx-w-Cy=0$. Hence the collineation in the plane p is of type V; dualistically the collineation in the bundle through III is also of type V. Thus it must have a pencil of invariant planes corresponding to the line of invariant points in p. The collineations in space are therefore of type XIII, and these form a five-parameter group of this type.

In like manner, when $n=0$ the two-dimensional collineations in p and through A are of type V and the three-dimensional collineations are of type XIII. They form a five-parameter subgroup of this type.

Each of these five-parameter subgroups of type XIII contains a singly infinite system of four-parameter subgroups and a doubly infinite system of three-parameter subgroups of type XIII. The fundamental group of XIII is three-parametered. The discussion of the details of these groups belongs more properly to the theory of type XIII and will be given in its proper place.

Subgroup of type XII in $G_6(Apl)$.—When $m=0$ and $n=0$, the one-dimensional transformations along l and in the pencil of planes through l are both identical; hence all points on l and all planes through l are invariant. The collineations in the planes through l are

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all of type V; hence the collineations in space are of type XII. There are ∞^4 such collineations in $G_6(\text{Apl})$, and they form a four-parameter subgroup of type XII.

Subgroups of type VII in $G_6(Apl)$.—When n, m and k are all zero, the transformation in the plane p is identical, and the remaining collineations are of type VII and form a three-parameter group. Dualistically there is a three-parameter group of type VII which leaves invariant every ray through A. This results when $m=0$, $n=0$, and $h=0$. The subgroups of these two three-parameter groups will not be discussed here.

THEOREM 4. The group $G_6(\text{Apl})$ contains two five-parameter subgroups of type XIII, one four-parameter subgroup of type XII, and two three-parameter subgroups of type VII.

The theory sketched in this paper holds equally well whether the collineations are real or complex.

Table of groups of type V.—The following is a complete list of the continuous groups of collineations of type V:

(1) $G_6(\text{Apl})$.
(2) $G_5(\text{Apl})\text{m}$.
(3) $G_5(\text{Apl})\text{n}$.
(4) $G_4(\text{Apl})\text{mn}$.
(5) $G_4(\text{Apl})\text{nh}$.
(6) $G_4(\text{Apl})\text{mk}$.
(7) $G_3(\text{Apl})\text{mnh}$.
(8) $G_3(\text{Apl})\text{mnk}$.
(9) $G_2(\text{Apl})\text{mnhk}$.
(10) $G_1(\text{Apl})$.

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COCCIDÆ OF KANSAS, IV.

Additional Species, Food-plants and Bibliography of Kansas Coccidæ, with Appendix on other Species Reported from Kansas.

BY S. J. HUNTER. With plate VIII.

A.—Additional Species.

Kermes pubescens Bogue. Plate VIII, fig. 1.

On white oak, Lawrence, Douglas county.

Kermes nivalis King and Ckll. Plate VIII, fig. 2.

On white oak, Lawrence, Douglas county.

Orthezia graminis Tinsley. Plate VIII, figs. 3, 4.

On goldenrod (*Solidago* sp.), Blue Rapids, Marshall county. Mrs. S. G. Cady, collector.

B.—Food-plants of Kansas Coccidæ.

In order to understand the significance or importance of the food-plants of Coccidæ, or scale-insects, some knowledge of the life and habits of the insect is necessary. Scale-insects are plant parasites and locate themselves upon the bark or outer covering of the plants. They have long, slender beaks, which they are able to insert into the tissues of the plants and draw therefrom the plant juices. Some scale-insects choose but a single host-plant, and others seem to be able to subsist upon a very great variety of plants. This adaptability to various food-plants has much to do with the numbers of the several species in existence. It is evident that if a species of insect has to depend exclusively upon a single plant variety, the chances of life for this insect would decrease with a decrease in numbers of the host; while, on the other hand, scale-insects which have the power to adapt themselves to a number of plants have greater chances of life and better opportunities for numerical increase. In animal parasitism the parasite tends to increase as the host increases. The increase of the parasite, however, is generally in a greater ratio than the increase of the host, so that the parasite frequently becomes so numerous as to destroy or greatly curtail the increase of the host, and then the parasite must succumb likewise, or adapt itself to new conditions. Such relations between host and parasite exist to a certain extent be-

[107]—K.U.Qr.—A x 3—July, '01.

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tween the scale-insects and their respective hosts. A study of the food-plants, therefore, of the scale-insects, becomes a matter of considerable importance in determining the continuation of a species and the possibilities of its numerical increase. The insects herein discussed have been found on certain food-plants in Kansas. They have likewise been found by other authorities on other food-plants in other parts of the globe. A record of each of these discoveries is given in the following pages:

***Aspidiotus forbesi* Johns.**

Honey-locust, *Gleditschia tricanthos* (Johns.), Ckll., Proc. Nat. M., XIX, p. 738.
Peach, *Prunus*, Ckll., ibid., p. 740.
Apricot, *Prunus armeniaca*, Johns., Ent. News, p. 151 (1896).
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Ash, Osborn, Proc. Iowa Acad. Sci., p. 229 (1897).
Crab-apple, Hunter, K. U. Quart., VIII., No. 1, p. 4 (Jan. 1899).
Pear, Johns., Ill. Sta. Lab. Nat. Hist., IV, p. 381.
Plum, ibid.
Apple, ibid.
Quince, ibid.
Currant, ibid.
Wild and cultivated cherry, *Amygdalus persica*, Leonardi, Riv. di Pat. Veg., p. 43 (1897).
Acer froxinus, ibid.
Staphylea trifoliata, ibid.

***Aspidiotus ancylus* Putnam.**

Linden, Comstock, 2d Corn. Univ. Rept., p. 140.
Box-elder, *Negundo* sp., Ckll., Proc.Nat. M., XIX, p. 735.
Apricot, *Prunus armeniacum*, Ckll., Proc. Nat. M., XIX, p. 741.
Plum, *Prunus domestica*, in Santa Fé, N. M.. Ckll., ibid.
Black currant, *Ribes* sp., Ckll., Am. Nat., p. 731 (1895).
Oaks, Comstock, 2d Corn. Univ. Rept., p. 140.
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Ilex verticillata, Felt., Bull. N. Y. Mus., VI, No. 31, p. 617 (1900).
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Mountain ash, ibid.
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Osage orange, ibid.
Hackberry, ibid.
Bladder-nut, ibid.
Ash, ibid.
Chestnut, in U. S. Dept. Agr. Coll. Howard.
Cratægus, ibid.
Elagnus reflexa, ibid.
Lonicera, ibid.
Syringa, ibid.
Prunus pissardi, ibid.

Aspidiotus uvæ Comst.

Grape, Comst., 2d Rept. Dept. Ent. Cor. Exp. Sta., p. 71, 1883.
Hickory, ibid.

Aspidiotus osborni Newell.

Quercus alba, Hunter, K. U. Quart., vol. VIII, No. 1, p. 6.
Ironwood, *Ostrya virginica*, Newell, Cont. Iowa St. Col. Agr., No. 3, p. 7.

Aspidiotus ulmi Johns.

White elm, *Ulmus americana*, Johns., Ill. St. Lab. Nat., vol. IV, art. 13, p. 388.
Slippery or Red elm, *Ulmus fulva*, Hunter, K. U. Quart., VIII, No. 1, p. 6.
Catalpa, Hunter, K. U. Quart., VIII, No. 1, p. 6.

Aspidiotus fernaldi Ckll., subsp. *albiventer*.

Maple, *Acer* sp., Hunter, K. U. Quart., VIII, No. 1, p. 7.

Aspidiotus obscurus Comst.

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Black oak, *Quercus* sp., Hunter, K. U. Quart., VIII, No. 1, p. 7.
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Aspidiotus juglans-regiæ Comst.

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Rhubarb, ibid.
Hemp, ibid.
Lamb's-quarters, ibid.
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Beggar-ticks, ibid.
Goose-foot, ibid.
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Sunflower, ibid.
Weeping willow, Smith, Rept. N. J. Agr. Col. Exp. Sta., p. 547, 1896.
Laurel-leaved willow, ibid.
Kilmarnock willow, ibid.
Linden, ibid.
English walnut, ibid.
Flowering currant, ibid.
Euonymus, ibid.
Gooseberry, ibid.
Persimmon, Ebenaceæ, ibid.
Acacia, Leguminoseæ, ibid.
Elm, ibid.
Osage orange, ibid.
Pecan, ibid.
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*Those succeeded by a star were kindly furnished by Mr. Kotinsky, through Dr. Howard.

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†As *A. circularis*, n. sp., but according to C. L. Marlatt MS. is *A. ancyclus*.

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The following synonymy is taken from C. L. Marlatt's MSS. of March 2, 1900:

Pergandei Comst. (merges into *proteus* Curt.)
Syn. var. *camelliæ* Comst.
" var. *crotonis* Ckll.
" var. *affinis* Newst.
" var. *calianthina* B. & L. (not seen; ? var. *theæ* Ckll.)
" var. *theæ* Ckll. (? *calianthina* B. & L.)
" (?) *dryandræ* Full.
" var. *euonymi* Ckll.
" *myrtus* Mask.
" (?) *pittaspori* Mask.
" *sinensis* Mask.
" var. *viridis* Ckll.
" var. *virescens* Mask.
" *viridis* Full.

Parlatoria pergandei Morgan, La. Sta., Bull. 28, 2d ser., pp. —, (18—).
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Parlatoria proteus Curt., var. *pergandei* Comst., King. Can. Ent., vol. —, p. 228.
Parlatoria pergandei Reh., Zeitschrift für Entom., vol. V, p. 162, June, 1900.*
do Ckll., Amer. Nat., July, 1897, p. 592.*
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Kermes nivalis.

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Kermes pubescens.

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Psyche, p. 80, July, 1900.
do Ckll, Psyche, IX, p. 44, Apr. 1900.*

Orthesia graminis.

Orthesia graminis Tinsley, Can. Ent., vol. 30, No. 1, p. 13, (1898).

NOTE.—To the list of food-plants Miss Etta Willett, a student of this department, added a number, an exact account of which was not taken at the time.

APPENDIX.

Other Coccidæ Reported from Kansas.

Kermes concinnulus Ckll., Cockerell, on oak, Can. Ent., p. 172, (1898).
Aspidiotus marlatti Parrott, on *Andropogon scoparius* and *Andropogon furcatus*, Can. Ent., p. 282, (1899).
Antonina nortoni Parrott and Ckll., on *Bouteloua racemosa*, Can. Ent., Oct. (1899).
Lecanium longulum Dougl., Parrott, Industrialist, p. 39, (1899).
Lecanium pruinosum Comst., ibid.
Aspidiotus cyanophylli Sign., ibid.
Aulacaspis boisduvalii Sign., ibid.
Parlatoria proteus Curt., ibid.
Aspidiotus helianthi Parrott, Can. Ent., vol. 31, p. 176 (1899).
Antonina bouteloucæ Parrott, on *Bouteloua hirsuta*, Parrott, Kan. Agr. Coll. Bull. No. 98, p. 138, (1900).
Antonina purpurea Sign., on *Milium* and *Agripyrum*, ibid.
Antonina graminis Parrott, on *Eragrotis trichodes*, *Bulbilis dactyloides*, *Paspalum ciliatifolium*, ibid., p. 140.
Gymnococus nativus Parrott, on *Sporobolus cryptandrus*, ibid., p. 143.
Pseudolecanium obscurum Parrott, on *Androgopon scoparius* and *Sporobolis longifolius*, ibid., p. 145.
Pseudolecanium californicum Ehrhorn, on *Androgopon furcatus*, ibid., p. 145.
Ericoccus kemptonia Parrott, ibid., p. 144.
Pulvinaria hunteri, on maple, King, MS.

LABORATORY OF COMPARATIVE ZOOLOGY AND ENTOMOLOGY,
July, 1901.

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FIG. 1.—*Kermes pubescens* on *Quercus alba*, Lawrence.

FIG. 2.—*Kermes nivalis* on *Quercus alba*, Lawrence.

FIG. 3.—Ventral view of *Orthezia graminis* on goldenrod (*Solidago* sp.), without posteriorly elongated egg sac. Mrs. S. G. Cady, col., Blue Rapids, Marshall county.

FIG. 4.—Dorsal view of *Orthezia graminis*, showing posteriorly elongated egg sac.

Photographs by the author.

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KANSAS UNIVERSITY QUARTERLY.

(Vol. X, No. 4—October, 1901.)

SERIES A.—SCIENCE AND MATHEMATICS.

CONTENTS.

I.—Bibliography of Scientific Publications by Members of the University of Kansas, ... *First Supplement.*

II.—List of Publications Received in Exchange for the Kansas University Quarterly.

III.—Contents of Kansas University Quarterly, . . *Volumes I-X.*

IV.—Index of Authors to Kansas University Quarterly, *Volumes I-X.*

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BIBLIOGRAPHY OF SCIENTIFIC PUBLICATIONS BY MEMBERS OF THE UNIVERSITY OF KANSAS.

FIRST SUPPLEMENT.

THERE was published in this journal, series A, Volume VIII, No. 4, October, 1899, a bibliography of the scientific publications by members of the University of Kansas. In the present supplementary list this bibliography is corrected in a few places and brought up to date.

Aldrich, JOHN M.

B. S. (South Dakota Agricultural College, 1888); M. S. (same, 1891, and University of Kansas, 1893). Professor of Zoology and Entomologist of Agricultural Experiment Station, University of Idaho, 1893.

1892 — 1. A New Genus and Species of Tabanidæ; Psyche, pp. 236, 237, 1 fig.
2. New Species of Phora; Canadian Entomologist, pp. 142–146, figs.
3. The Systematic Position of the Diptera; Science, New York.
4. Revision of the Genera Dolichopus and Hygroceleuthus; this journal, pp. 1–26, 1 pl.
5. New Genera and Species of Psilopinæ; this journal, pp. 47–50.
6. The Dolichopodid Genus Liancalus Loew; Psyche, pp. 569–571.

1894 — 7. New Genera and Species of Dolichopodidæ; this journal, pp. 151–157.
8. Courtship among the Flies; Amer. Nat., pp. 35–37.

1895 — 9. The Tipulid Genera Bittacomorpha and Pedicia; Psyche, pp. 200, 202, 1 fig.

1896—10. A Collection of Diptera from Indiana Caves; 21st Annual Report of the Geology and Natural Resources of Indiana, 1 fig.
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12. On the Diptera of St. Vincent (Dolichopodidæ and Phoridæ); Trans. Ent. Soc. Lond., pp. 309–345 and 435–439.

1899—13. A Balloon-making Fly (published with L. A. Turley); Amer. Nat., pp. 809–812, with illustrations.
14. Goniops and other Synonyms; Ent. News, p. 531.

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Bailey, Edgar Henry Summerfield.

(Continued from vol. viii A, p. 140.)

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54. The New Chemical Laboratory of the University of Kansas; Science, N. S., xii, No. 313, Dec. 28, pp. 997–1001, fig. 6.

55. On the Softening of Public Water-supplies, with some Analyses of a Recent Process; Proc. Kans. Gas, Water and Elec. Lt. Assoc., pp. 18–26.

1901—56. Experiments on the Relative Heating Power of Coal and Illuminating Gas; Trans. Kans. Acad. Sci., xvii, pp. 35–38, fig 1.

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58. The Development of the Incandescent Gas Lighting Industry; Proc. Kans. Gas, Water and Elect. Lt. Assoc., pp. 22–29.

Bartow, Edward.

(Continued from vol. viii A, p. 140.)

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1900—5. Classification of Organic Remedies; Organic Materia Medica and Pharmacognosy, by Prof. L. E. Sayre, Phila., 1900, pp. 26–36.

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(Continued from vol. viii A, p. 140.)

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1899—9. Description of Some New Forms of Pseudomonotis from the Upper Coal Measures of Kansas; this journal, viii, pp. 79–84, pls. viii, ix.

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12. Carboniferous Invertebrates; Univ. Geol. Surv. Kans., vi, pp. 1–187, pls. i–xxii, 11 figs.

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15. Fauna of the Permian of Central United States, I; Trans. Kans. Acad. Sci., xvii, pp. 185–189, pls. xiii, xiv.

Blackman, Maulsby Willett.

A. B. (University of Kansas, 1901).

1901—1. Spermatogenesis of the Myriapods, I; this journal, x A, pp. 61–76.

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Blake, Lucien Ira.

(Continued from vol. viii A, p. 141.)

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(Continued from vol. viii A, p. 142.)

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Crane, Walter Richard.

A. B. (University of Kansas, 1895, and A. M., 1896); Ph. D. (Columbia, 1901). Instructor, Lawrence High School, 1896–'97; Beloit High School, 1897–'98; Instructor of Manual Training, city schools, Janesville, Wis., 1898–'99; Assistant Professor of Mining, 1899.

1896 — 1. Curvimeter; this journal, iv, p. 121.

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6. Concentrating Zinc-Lead Ores; Mines and Minerals, Sept., 1901, p. 73.

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Diemer, Hugo.

M. E. (Ohio State University, 1896). With Bullock Electric Manufacturing Company, Cincinnati, and Westinghouse Electric and Manufacturing Company, Pittsburg, 1896–'99; in charge of Mechanical Department A. and M. College, Greensboro, N. C., 1899–1900; Assistant Professor of Mechanical Engineering, Michigan Agricultural College, 1900–'01; Associate Professor of Mechanical Engineering, 1901.

1900 — 1. The Purchasing Department; Eng. Mag.

2. The Classification of Shop Orders; Eng. Mag.

3. The Production Department: Bills of Material; Eng. Mag.

4. The Production Department: Store-room Management; Eng. Mag.

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(Continued from vol. viii A, p. 141.)

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Harris, J. Arthur.

A. B. (University of Kansas, 1901). Graduate Student, University of Kansas, 1901; Botanical Assistant, Missouri Botanical Garden, 1901.

1900—1. Annotated Catalogue of the Crayfishes of Kansas; this journal, ix A, pp. 263–274.

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1901—3. Notes on the Habits of Cambarus immunis Hagen; Amer. Nat., xxxv, pp. 187–191.

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6. Normal and Teratological Thorns of Gleditschia triacanthos L., with 5 pls.; Trans. Acad. Sci. St. Louis, xi, pp. 215–222.

Havenhill, L. D.

Ph. C., 1893, Ph. M., 1894 (University of Michigan). Assistant in Pharmacy and Pharmacognosy, University of Michigan, 1893–'94; Analytical Chemist with Dr. A. B. Lyons, Honolulu, H. I., 1894–'95; Pharmacist with J. B. Chase, Aurora, Ill., 1895–'96; Chemist with the Chicago & Aurora Smelting and Refining Company, Aurora, Ill., 1896–'99; Assistant Professor of Pharmacy, University of Kansas, 1899.

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(Continued from vol. viii A, p. 146.)

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A. B. (University of Kansas, 1900). Instructor in Chemistry, 1901.

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Powell, Emery H.

B. M. E. (University of Wisconsin, 1891). Draftsman and Erecting Engineer for the Hercules Ice Machine Company, Aurora, Ill., 1892–'96; Chief Draftsman and Assistant Superintendent Jobbins & Van Ruymbeke (manufacturers glycerine machinery), Aurora, Ill., 1896–'99; Draftsman and Designer of Beet-sugar Machinery with the Dayton Globe Ironworks Company, Dayton, Ohio, 1899–1900.

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Rogers, Austin Flint.

A. B. (University of Kansas, 1899); A. M. (1900). Graduate Student and Assistant in Mineralogy 1899–1900; Assistant Geologist, University Geological Survey of Kansas, 1898–'00; Fellow in Mineralogy, Columbia University, New York city, 1900–'02.

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Sellards, E. H.

A. B. (University of Kansas, 1899); A. M. (1900). Assistant, University Geological Surveyor of Kansas, 1900, 1901; Graduate Student Yale University, 1901.

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Snow, Martha B.

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Sutton, Walter S.

A. B. (Kansas University, 1900); A. M. (1901). Instructor in Zoölogy, Kansas University, 1899; Instructor in Zoölogy and History, 1900; Fellow in Zoölogy, Columbia University, 1901.

1900—1. The Spermatogonial Divisions in Brachystola magna; this journal, ix, pp. 135–168.

2. The Melanopli of Kansas (with S. J. Hunter); Psyche, ix, p. 290.

Ward, Frank E.

Superintendent of Fowler Shops and Shop Instructor; Instructor in Machine Work and Mechanical Methods and Practice.

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——— State Mining Bureau. Bulletins, Biennial Reports.

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COLORADO.

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Colorado Springs, Colorado College. Studies.

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——— Connecticut Academy of Sciences. Transactions.

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——— American Monthly Microscopical Journal.

——— Biological Society of Washington. Proceedings.

——— Entomological Society of Washington. Proceedings.

——— Mathematical Magazine.

——— Philosophical Society of Washington. Bulletin.

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——— United States Naval Observatory. Publications.

——— Commissioner of Education. Publications.

——— United States Department of Agriculture. Publications.

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GEORGIA.

Atlanta, Geological Survey of Georgia. Bulletins, Administrative Reports.

ILLINOIS.

Champaign, University of Illinois. University Studies.

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——— Western Society of Engineers. Journal.
Peoria, Illinois Society of Engineers and Surveyors. Proceedings.
Rock Island, Augustana College. Publications.
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Indianapolis, Indiana Academy of Sciences. Proceedings.
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IOWA.

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Emporia, State Normal Monthly.
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MARYLAND.

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MINNESOTA.

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——— Minnesota Academy of Natural Sciences. Bulletin.

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Columbia, University of Missouri.
Jefferson City, Missouri Geological Survey. Reports.
Springfield, The American Mathematical Monthly.
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——— Nebraska Historical Society. Proceedings and Transactions.

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NEW JERSEY.

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Newark, New Jersey Historical Society. Proceedings.
Princeton, Princeton University. Bulletin.
——— Princeton University. Contributions to Psychology.
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——— New York State Geological Survey. Annual Reports.
——— State Library. Bulletin of the New York State Museum, Extension Bulletins.
Brooklyn, Brooklyn Institute of Arts and Sciences. Year-book.
Buffalo, Buffalo Society of Natural History. Bulletins.
Ithaca, Cornell University. Bulletins of American Paleontology, Studies in Classical Philology, Science Bulletins, Library Catalogues.
New Brighton, Natural Science Association of Staten Island. Proceedings.
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——— Engineering News.
——— American Mathematical Society. Bulletin.
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——— American Society of Civil Engineers. Proceedings.
——— Association of Engineering Societies. Journal.
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Granville, Denison Scientific Association. Bulletin.
Oberlin, Oberlin College Publications.
Wooster, Wooster College. Post Graduate and Wooster Quarterly.

OREGON.

Eugene, University of Oregon. Publications.

PENNSYLVANIA.

Bryn Mawr, Bryn Mawr College. Publications.
Philadelphia, The Entomological Student.
——— Engineers' Club of Philadelphia. Journal.
——— University of Pennsylvania. Publications.
——— The Nautilus.
——— Wagner Free Institute of Science. Transactions.
——— American Entomological Society. Transactions.
——— Geographical Society of Philadelphia. Bulletin.
——— The Franklin Institute. Journal.
——— American Philosophical Society. Proceedings.
——— Philadelphia Academy of Natural Sciences. Proceedings.
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Scranton, Mines and Minerals.
Wilkesbarre, Wyoming Historical and Geological Society. Proceedings and Collections.

RHODE ISLAND.

Providence, Brown University. Publications.

TENNESSEE.

Nashville, Vanderbilt University Quarterly.

TEXAS.

Austin, Texas State Historical Association. Quarterly.
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Richmond, The Virginia Medical Semi-monthly.

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——— Wisconsin Geological and Natural History Survey. Bulletins.
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WYOMING.

Laramie, University of Wyoming. Bulletins.

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Halifax, Nova Scotian Institute of Science. Proceedings.
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——— Geological Survey of Canada. Bulletins, Annual Reports.
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MEXICO.

Mexico, Sociedad Cientifica "Antonio Alzate." Memorias y Revista.
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Toluca, Instituto Cientifico y Literario "Porfirio Diaz." Boletin.

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CENTRAL AMERICA.

San José, Museo Nacional de Costa Rica.
——— Instituto Fisico Geografico. Anales, etc.

ARGENTINA.

Buenos Aires, Universidad de Buenos Aires. Anales.
——— Museo Nacional de Buenos Aires. Anales, Communicaciones.
——— Instituto Geográfico Argentino. Boletin.
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——— Museo de La Plata. Revista.

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Rio de Janeiro, Museu Nacional. Archivas.
——— Sociedad de Geografia de Rio de Janeiro. Revista.
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CHILI.

Santiago, Sociedad Cientifica. Alemana, Verhandlungen.
——— Sociedad Cientifica de Chile.
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URUGUAY.

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AUSTRIA.

Insbruck, Tiroler Landes-Museum Ferdinandeum. Zeitschrift.
Cracow, Academie des Sciences. Bulletin International.
Lemberg, Academie der Wissenschaften. Chronik.
Prag, Böhmische Mathematische Gesellschaft. Casopis, Sbornik.
——— Böhmische Gesellschaft der Wissenschaften. Jahresberichte, Sitzungsberichte Mathematische und Naturwissenschaftliche Klasse.
Vienna, K. K. Geologische Reichsanstalt. Verhandlungen, Jahrbuch.
——— Monatshefte für Mathematik und Physik.
——— Naturwissenschaftlicher Verein der Universität Wien. Mittheilungen.
——— K. K. Naturhistorisches Hof Museum. Annalen.
——— K. K. Zoologisch-Botanische Gesellschaft. Verhandlungen.
——— Kaiserliche Akademie der Wissenschaften. Sitzungsberichte.

BELGIUM.

Brussels, Académie Royal des Sciences, des Lettres et des Beaux Arts de Belgique.
——— Société Royale Malacologique. Annales, Proces-Verbaux.
——— Société Entomologique de Belgique. Annales.
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DENMARK.

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ENGLAND.

Cambridge, Cambridge Philosophical Society. Proceedings, Transactions.
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Halifax, Yorkshire Geological and Polytechnic Society. Proceedings.
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——— Geological Society. Quarterly Journal.
——— Royal Society. Proceedings.
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Newcastle, Institute of Mining and Mechanical Engineers.
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CONTENTS OF VOLUMES I TO X OF THE KANSAS UNIVERSITY QUARTERLY.

VOLUME I.

No. 1.

		PAGE.
Kansas Pterodactyls, I	S. W. Williston.	1
Kansas Mosasaurs, I	S. W. Williston and E. C. Case.	15
Notes and Descriptions of Syrphidæ	W. A. Snow.	33
Notes on Melitera dentata Grote	V. L. Kellogg.	39
Diptera Brasiliana, II	S. W. Williston.	43

No. 2.

Unicursal Curves by Method of Inversion	H. B. Newson.	47
Foreign Settlements in Kansas	W. H. Carruth.	71
The Great Spirit Spring Mound	E. H. S. Bailey.	85
On Pascal's Limacon and the Cardioid	H. C. Riggs.	89
Dialect Word-list	W. H. Carruth.	95

No. 3.

On the Apioceridæ and their Allies	S. W. Williston.	101
Diptera Brasiliana, III	S. W. Williston.	119
Notes on Some Diseases of Grasses	W. C. Stevens.	123
Modern Higher Algebra	E. Miller.	133
Dialect Word-list, II	W. H. Carruth.	137
Maximum Bending Moments for Moving Loads in a Parabolic Arch-rib Hinged at the Ends	E. C. Murphy.	143

No. 4.

Penology in Kansas	F. W. Blackmar.	155
Bibliography of Municipal Government in the United States	F. H. Hodder.	179

VOLUME II.

No. 1.

Revision of the Genera Dolichopus and Hygroceleuthus	J. M. Aldrich.	1
Present Status of the Street-paving Problem in Kansas	E. C. Murphy.	27
Maximum Load on a Lintel	E. C. Murphy.	31
The Trisection of an Angle	A. L. Candy.	35
New Genera and Species of Psilopinæ	J. M. Aldrich.	47

No. 2.

The Sclerites of the Head of Danais archippus Fad	V. L. Kellogg.	51
New or Little-known Diptera	S. W. Williston.	59
Kansas Pterodactyls, II	S. W. Williston.	79
Kansas Mosasaurs, II	S. W. Williston.	83
Linear Geometry of the Cubic and Quartic, I	H. B. Newson.	85
On the Delicacy of the Sense of Taste among Indians	E. H. S. Bailey.	95

[169]—K.U.Qr.—A x 4—October, '01.

Digitized by Google

VOLUME I—CONCLUDED.

No. 3.

Report of Field Work in Geology, Erasmus Haworth, M. Z. Kirk, and W. H. H. Piatt. 99
A Geological Reconnoisance in Southwest Kansas and No Man's Land.....E. C. Case. 141
Traces of a Glacier at Kansas City, Mo.....E. C. Case. 149
New Genera and Species of Dolichopodidæ.....J. M. Aldrich. 151
Description of North American Trypetidæ, with Notes, part I..W. A. Snow. 159

No. 4.

The Control of the Purse in the U. S. Government.....E. D. Adams. 175
The Character and Opinions of William Langland.....E. M. Hopkins. 233
Restoration of a Rhinoceros (*Aceratherium fossiger*).....S. W. Williston. 289

VOLUME III.

No. 1.

Verterate Remains from Lowermost Cretaceous.....S. W. Williston. 1
A New Turtle from the Benton Cretaceous.....S. W. Williston. 5
Notes on Uintacrinus socialis Grinnell.....S. W. Williston. 19
Restoration of Platygonus.....S. W. Williston. 23
The Genus Dolichomyia, with Description of a New Species, S. W. Williston. 41
The Taxonomic Value of the Scales of the Lepidoptera..Vernon L. Kellogg. 45
A Chemical Examination of the Water of the Kaw and its Tributaries..... E. H. S. Bailey and E. C. Franklin. 91

No. 2.

The Hessian, Jacobian, Steinerian, in Geometry of one Dimension.....H. B. Newson. 103
Irrigation in Western Kansas.....E. C. Murphy. 117
Birds of Finney County, Kansas.....H. W. Menke. 129
The Prothorax of Butterflies.....May H. Wellman. 137
American Platypezidæ.....W. A. Snow. 143
A Special Class of Connected Surfaces.....Arnold Emch. 153
Foreign Settlements in Kansas.....W. H. Carruth. 159

No. 3.

New or Little-known Extinct Vertebrates.....S. W. Williston. 165
Cnephalia and its Allies.....W. A. Snow. 177
A New Species of Pelecocera.....W. A. Snow. 187
Exotic Tabanidæ.....S. W. Williston. 189
Chemical Analysis of Counterfeit Gold Dust..V. L. Leighton and H. P. Cady. 198
The Temperature Sense.....William Newton Logan. 201
American Platypezidæ.....W. A. Snow. 205

No. 4.

Semi-arid Kansas.....S. W. Williston. 209
Collection and Storage of Water in Kansas.....E. C. Murphy. 217
Diptera of Colorado and New Mexico.....W. A. Snow. 225
Supplementary List of North American Syrphidæ.....W. A. Snow. 249
Dialysis and Triptotricha.....S. W. Williston. 263
New Bombyliidæ.....S. W. Williston. 267
The Stratigraphy of the New Coal Measures.....Erasmus Haworth. 271
Division of the Kansas Coal Measures.....Erasmus Haworth. 291
The Coal Fields of Kansas.....Erasmus Haworth. 297

Digitized by Google

VOLUME IV.

No. 1.

Natural Gas and Coal Oil in Kansas.....E. H. S. Bailey. 1
Experiments in the Solution of the Labor Problem.....F. W. Blackmar. 15
The Servant-girl Problem.....Martha Boutelle Snow. 31
The Condition of Packing-house Employees.....A. E. Moody. 41
Notes on the Mandible of Ornithostoma.....S. W. Williston. 61
Notes of Air Resistance and Pressure.....E. C. Murphy. 63
The Coffeyville Explosion.....Erasmus Haworth. 67

No. 2.

Continuous Groups of Projective Transformations Treated Synthetically, H. B. Newson. 71
The Theoretical and Measured Pumping Power of Windmills...E. C. Murphy. 93
Two Remarkable Genera of Diptera.....S. W. Williston, 107
Involutoric Transformation of the Straight Line.....Arnold Emch. 111
On Toxotrypana of Gerstæcker.....W. A. Snow. 117

No. 3.

A Curvimeter.....W. R. Crane. 121
The Sands of the Kansas River Valley.....M. Z. Kirk. 125
Bibliography of North American Dipterology, 1878–1895....S. W. Williston. 129
Horsebacks in the Kansas Coal Measures.....W. R. Crane. 145
A Preliminary Report on the Glaciated Area of Kansas.....Earl G. Swem. 153
A Geological Section at Providence, Mo.....Alban Stewart. 161
Notes on the Discharge of the Kansas River at Lawrence, Kan., Since 1881, E. C. Murphy. 163
Supplementary Notes on the Article on Continuous Groups..H. B. Newson. 169
Fissicorn Tachinidæ.....S. W. Williston. 171
List of Asilidæ, Supplementary to Osten Sacken's Catalogue of North American Diptera, 1878–1895.....W. A. Snow. 173
Editorial Notes..... 191

No. 4.

On the Skull of Ornithostoma.....S. W. Williston. 195
Bibliography of the North American Diptera.....S. W. Williston. 199
Involutoric Collineation in the Plane and in Space.....Arnold Emch. 205
A Study of the Type of the Greek Epitaphios with Special Reference to the Oration in Thucydides.....David H. Holmes. 219
A New Species of Dinictis from the White River Miocene of Wyoming, Elmer S. Riggs. 237
Continuous Groups of Projective Transformations Treated Synthetically, H. B. Newson. 243

VOLUME V.

No. 1.

Projective Groups of Perspective Collineations in the Plane Treated Synthetically.....Arnold Emch. 1
Hoplophoneus occidentalis.....E. S. Riggs. 37
One of the Dermal Coverings of Hesperornis.....S. W. Williston. 53
The Duty of the Scholar in Politics.....Frank Heywood Hodder. 55

Digitized by Google

VOLUME V—CONCLUDED.

No. 2.

Continuous Groups of Projective Transformations Treated Synthetically.....H. B. Newson. 81
Theory of Compound Curves in Railroad Engineering.....Arnold Emch. 99
The Visual Perception of Distance.....John E. Rouse. 109
The Limitations of the Composition of Verbs, with Prepositions, in Thucydides.....David H. Holmes. 119
Editorial Notes.

VOLUME VI A.

No. 1.

Diptera Brasiliana, part IV.....S. W. Williston. 1
Restoration of Oreodon culbertsonii Leidy.....Alban Stewart. 13
Gypsum in Kansas.....G. P. Grimsley. 16
On the Chemical Composition of some Kansas Gypsum Rocks, E. H. S. Bailey and W. H. Whitten. 29
Restoration of Ornithostoma (Pteranodon).....S. W. Williston. 35
Notice on some Vertebrate Remains from the Kansas Permian.....S. W. Williston. 57
Table for the Calculation of Analyses, Edward Bartow and J. N. Macomb, jr. 59

No. 2.

Types of Projective Tranformations in the Plane and in Space, H. B. Newson. 63
A New Explosive Compound Formed by the Action of Liquid Ammonia upon Iodine.....H. P. Cady. 71
The Effect of Magnetism upon the Spectral Lines of Sodium, A. St. C. Dunstan, M. E. Rice, and C. A. Kraus. 78
Results of Windmill Tests.....E. C. Murphy. 89
Brachysaurus, a New Genus of Pythonomorpha.....S. W. Williston. 96
On the Extremities of Tylosaurus.....S. W. Williston. 97
Two New Species of Asilids from New Mexico.....Barnum Brown. 103

No. 3.

Restoration of Kansas Monasaurs.....S. W. Williston. 107
Salicylic Acid and Calcium Sulfite as Preservatives of Cider, E. H. S. Bailey and C. M. Palmer. 111
On the Composition of the Louisville Mineral Water.....E. H. S. Bailey. 117
The Myology of the Hind Leg of the Raccoon (Procyon lotor)..R. C. Gowell. 121
Notes on the Osteology of Bison antiquus Leidy.....Alban Stewart. 127
Two New Species of Syrphid Genera, Mixogaster Macq. and Ceria Farb.....Paul Hugo Isidor Kahl. 137

No. 4.

The Permian and Upper Carboniferous of Southern Kansas...C. S. Prosser. 149
The Range and Distribution of Mosasaurs, with Remarks on Synonymy.....S. W. Williston. 177
Some New Cirriped Crustaceans from the Niobrara Cretaceous of Kansas.....W. N. Logan. 187
Power of a Twelve Foot "Power" Windmill.....E. C. Murphy. 191
On New Canonical Forms of the Binary Quintic and Sextic, Bessie E. Growe. 201
On the Action of Sulphuric Acid upon Strychnine, in the Separation of this Alkaloid from Organic Matter, E. H. S. Bailey and Wm. Lange. 205
A New Labyrinthodont from the Kansas Carboniferous.....S. W. Williston. 209

Digitized by Google

VOLUME VI B.

No. 2.

The Use of Analysis in Logical Composition ..... E. M. Hopkins. 1
Dialect Word-list, III ..... W. H. Carruth. 51

No. 2.

Productive Cooperation in England ..... F. W. Blackmar. 59
Pronouns Used in Address in Lessing's Dramas,
W. H. Carruth and Eugene C. Alder. 65
Dialect Word-list, IV ..... W. H. Carruth and Paul Wilkinson. 85

No. 3.

The Duty of the State to the Scholar ..... Olin Templin. 87
The Pronouns Used in Address in Lessing's Dramas ..... Eugene C. Alder. 115

No. 4.

Notes on Brief-making ..... E. M. Hopkins. 127
Pronouns of Address in "The Idyls of the King" ..... W. H. Carruth. 159
Taxation in Kansas, part I ..... F. W. Blackmar. 171

VOLUME VII A.

No. 1.

Experiments in Judging the Direction of Sound ..... C. E. Shutt. 1
Experiments in Judging the Direction of Sound. L. D. Ikenberry, C. E. Shutt. 9
New Corals from the Kansas Carboniferous ..... J. W. Beede. 17
A Geological Map of Logan and Gove Counties ..... Geo. I. Adams. 19
A Contribution to the Knowlege of the Ichthyic Fauna of the Kansas Cretaceous ..... Alban Stewart. 21
Alternating Currents in Wheatstone's Bridge ..... M. E. Rice. 31
Adulterations of Buckwheat Flour Sold in the Lawrence Market ..... Marshall A. Barber. 37
The Designing of Cone Pulleys ..... Walter K. Palmer. 41

No. 2.

The Behavior of Kinoplasm and Nucleolus in the Division of Pollen Mother Cells of Asclepias cornuti ..... William C. Stevens. 78
Physiography of Southeastern Kansas ..... Geo. I. Adams. 87
Variations of External Appearance and Internal Characters of Spirifer cameratus Morton ..... J. W. Beede. 103
Apparatus to Facilitate the Process of Fixing and Hardening Material ..... William C. Stevens. 107
The Preparation and Use in Class Demonstration of Certain Cryptogamic Plant Material ..... Marshall A. Barber. 111

No. 3.

Individual Variations in the Genus Xiphactinus Leidy ..... Alban Stewart. 115
A Geological Reconnoissance in Grant, Garfield and Woods Counties, Oklahoma ..... Geo. I. Adams. 121
Normal Forms of Projective Transformations ..... H. B. Newson. 125
On the Skull of Xerobates (?) undata Cope ..... J. Z. Gilbert. 143
A Plan for Increasing the Capacity of the Steam-heating Plant of the Spooner Library, University of Kansas ..... Frank E. Ward. 149
The Hyperbolic Spiral ..... W. K. Palmer. 155
The Sacrum of Morosaurus ..... S. W. Williston. 173

Digitized by Google

VOLUME VII A—CONCLUDED.

No. 4.

Some Notes on the Genus Saurodon and Allied Species.....Alban Stewart. 177
Notes on Campophyllum torquium Owen, and a New Variety of Monopteria gibbosa Meek and Worthen .....J. W. Beede. 187
A Preliminary Description of Seven New Species of Fish from the Cretaceous of Kansas .....Alban Stewart. 191
Refractive Index and Alcohol-solvent Power of a Number of Clearing and Mounting Media.....C. E. McClung. 197
On Some Turtle Remains from the Fort Pierre.....George Wagner. 201
Parasite Influence on Melanoplus .....S. J. Hunter. 205
A Graphical Method of Constructing the Catenary.....Walter K. Palmer. 211
Preliminary Notice on the Correlation of the Meek and Marcou Section at Nebraska City, Neb., with the Kansas Coal Measures.....J. W. Beede. 231

VOLUME VII B.

Nos. 1 and 2.

Notes on Piers Plowman.....E. M. Hopkins. 1
Economic and Social Influence of Irrigation.....F. W. Blackmar. 27

No. 3.

The Tone of Literature and the Writer's Responsibility.....A. G. Canfield. 39

No. 4.

The Sequence of Tenses in Latin .....A. T. Walker. 57
Some Prehistoric Ruins in Scott County, Kansas .....S. W. Williston. 109

VOLUME VIII.

No. 1.

The Coccidæ of Kansas.....S. J. Hunter. 1
The Characters of *Bison occidentalis*, the Fossil Bison of Kansas and Alaska.....F. A. Lucas. 17
A Preliminary Description of the Opercular and other Cranial Bones of Xiphactinus Leidy.....Alban Stewart. 19
Diphtheria in Kansas.....Marshall A. Barber. 23
Pachyrhizodus minimus, a New Species of Fish from the Cretaceous of Kansas .....Alban Stewart. 37
Some Additional Characters of the Mosasaurs.....S. W. Williston. 39

No. 2.

The Five Types of Transformations of the Plane.....Henry B. Newson. 43
The Coccidæ of Kansas, II.....S. J. Hunter. 67
Description of Some New Forms of Pseudomonotis from the Upper Coal Measures of Kansas .....J. W. Beede. 79
Note on the Yellow Helium Line .....A. St. C. Dunstan and M. E Rice. 85
Some Additions to the Cretaceous Invertebrates of Kansas....W. N. Logan. 87
On *Tetracaulodon shepardii* Cope .....George Wagner. 99
Cuprogoslarite, a New Variety of Zinc Sulphate.....Austin F. Rogers. 105

Digitized by Google

VOLUME VIII—Concluded.

No. 3.

Notice of Three New Cretaceous Fishes, with Remarks on the Saurodontidæ Cope.....Alban Stewart. 107
A New Genus of Fishes from the Niobrara Cretaceous.....S. W. Williston. 113
Notes on the Osteology of *Anogmius polymicrodus* Stewart, Alban Stewart. 117
New Fossils from the Kansas Coal Measures.....J. W. Beede. 123
New and Little-known Pelecypods from the Coal Measures, J. W. Beede and Austin F. Rogers. 131
Note on the Distribution of the Cheyenne Sandstone.....C. S. Prosser. 135

No. 4.

Bibliography of Scientific Publications by Members of the University of Kansas..... 138
A New Species of Sagenodus from the Kansas Coal Measures, S. W. Williston. 175
Normal Ankerite from Phelps County, Missouri.....Austin F. Rogers. 183
Notes on the Coraco-scapula of Eryops Cope.....S. W. Williston. 185

VOLUME IX.

No. 1.

A New Genus and New Species of Bryozoans from the Coal Measures of Kansas and Missouri.....Austin F. Rogers. 1
Two New Crinoids from the Kansas Carboniferous.....J. W. Beede. 21
Some Fish Teeth from the Kansas Cretaceous.....S. W. Williston. 27
Note on the Permian Flora of Kansas.....E. H. Sellards. 63
On the Construction of Collineations.....H. B. Newson. 65
The Spermatocyte Divisions of the Acrididæ.....C. E. McClung. 73

No. 2.

Coccidæ of Kansas, III.....S. J. Hunter. 101
The Stratigraphy and Invertebrate Faunas of the Jurassic Formation in the Freeze-out Hills of Wyoming.....W. N. Logan. 109
The Spermatogonial Divisions in *Brachystola magna*...Walter B. Sutton. 135
Annotated List of the Minerals Occurring in the Joplin Lead and Zinc District.....Austin F. Rogers. 161

No. 3.

Collateral Circulation in the Cat after Ligation of the Post-cava.....Ida H. Hyde. 167
Occurrence of the Bryozoan Genus *Rhabdomeson* in America, Austin F. Rogers. 173
Stratigraphy of the McCann Sandstone.....C. N. Gould. 175
A New Genus of Ferns from the Permian of Kansas.....E. H. Sellards. 179
A Reconnaissance in the Blue Valley Permian.....J. W. Beede. 191
South American Muscidæ in the Collection of S. W. Williston, Gary de N. Hough. 203

No. 4.

Coal Measures Faunal Studies, I.....J. W. Beede and Austin F. Rogers. 233
Microscopic Comparison of Samples of White Arsenic.....Edward Bartow. 255
The Detection of Arsenic, Antimony, and Tin.....Hamilton P. Cady. 259
Annotated Catalogue of the Crayfishes of Kansas.....J. Arthur Harris. 263

Digitized by Google

VOLUME X.

No. 1.

Permian Plants—Tæniopteris of the Permian of Kansas.....E. H. Sellards. 1
On the Group of 216 Collineations in the Plane.....H. B. Newson. 13

No. 2.

On the Group and Subgroups of Real Collineations Leaving a Tetrahedron Invariant (A New Theory of Collineations in Space, I).....H. B. Newson. 13
The Dimorphism of Cambarus, I.....J. Arthur Harris. 49
Spermatogenesis of the Myriapods, I.....M. W. Blackman. 61

No. 3.

Action of Liquid Ammonia on Acid Chlorids and Esters, Edward Bartow and D. F. McFarland. 79
A New Theory of Collineations in Space, II.....H. B. Newson. 87
A New Theory of Collineations in Space, III .....H. B. Newson. 99
Coccidæ of Kansas, IV.....S. J. Hunter. 107

No. 4.

Bibliography of Scientific Publications by Members of the University of Kansas, First Supplement..... 149
List of Publications Received in Exchange for the Kansas University Quarterly 159
Contents of Kansas University Quarterly, Volumes I–X..... 169
Index of Authors to Kansas University Quarterly, Volumes I–X..... 177
Subject Index to Kansas University Quarterly, Volumes I–X..... 187

Digitized by Google

INDEX OF AUTHORS, VOLS. I TO X OF THE KANSAS UNIVERSITY QUARTERLY.

ADAMS, E. D.

On the Control of the Purse in the United States Government, ii, 175.
On the Partition of Africa, viii B, 1.

ADAMS, G. I.

A Geological Map of Logan and Gove Counties, vii A, 19.
Physiography of Southeastern Kansas, vii A, 87.
A Geological Reconnoisance in Grant, Garfield and Woods Counties, Oklahoma, vii A, 121.
Bibliography, viii A, 137.

ALDER, E. C.

Pronouns Used in Address in Lessing's Dramas (with W. H. Carruth), vi B, 65.
Pronouns Used in Address in Lessing's Dramas, II, vi B, 115.

ALDRICH, J. M.

Revision of the Genera *Dolichopus* and *Hygroceleuthus*, ii, 1.
New Genera and Species of Psilopinæ, ii, 47.
New Genera and Species of Dolichopodidæ, ii, 151.
Bibliography, x A, 149.

BAILEY, E. H. S.

On the Delicacy of the Sense of Taste among Indians, ii, 95.
A Chemical Examination of the Water of the Kaw and its Tributaries (with E. C. Franklin), iii, 91.
Natural Gas and Coal Oil in Kansas, iv, 1.
On the Chemical Composition of Some Kansas Gypsum Rocks (with W. H. Whitten), vi A, 29.
Salicylic Acid and Calcium Sulfite as Preservatives of Cider (with C. M. Palmer), vi A, 111.
On the Composition of the Louisville Mineral Water, vi A, 117.
On the Action of Sulphuric Acid upon Strychnine, in the Separation of this Alkaloid (with W. Lange), vi A, 205.
Bibliography, viii A, 138.
Bibliography, continued, x A, 150.

BARBER, M. A.

Adulterations of Buckwheat Flour Sold in the Lawrence Market, vii A, 37.
The Preparation and Use in Class Demonstration of Certain Cryptoganic Plant Material, vii A, 111.
Diphtheria in Kansas, viii A, 23.
Bibliography, viii A, 140.

BARTOW, E.

Table for the Calculation of Analyses (with J. N. Macomb, jr.), vi, A, 59.
Microscopic Comparison of Samples of White Arsenic, ix, A, 255.
Action of Liquid Ammonia on Acid Chlorids and Esters (with McFarland), x.
Bibliography, viii A, 140.
Bibliography, continued, x A, 150.

Digitized by Google

J. W. BEEDE.

New Corals from the Kansas Carboniferous, vii A, 17.
Variation of External Appearance and Internal Characters of *Spirifer cameratus* Morton, vii A, 103.
Notes on *Campophyllum torquium* Owen and a New Variety of *Monopteria gibbosa* Meek and Worthen, vii A, 187.
Preliminary Notice on the Correlation of the Meek and Marcou Section at Nebraska City, Neb., with the Kansas Coal Measures, vii A, 231.
Description of Some New Forms of *Pseudomonotis* from the Upper Coal Measures of Kansas, viii A, 79.
New Fossils from the Kansas Coal Measures, viii, A, 123.
New and Little Known Pelecypods from the Kansas Coal Measures (with A. F. Rogers), viii A, 131.
Two New Crinoids from the Kansas Carboniferous, ix A, 21.
A Reconnaissance in the Blue Valley Permian, ix A, 191.
Coal Measure Faunal Studies, I (with A. F. Rogers), ix A, 233.
Bibliography, viii, A, 140.
Bibliography, continued, x A, 150.

BLACKMAN, M. W.

Spermatogenesis of the Myriapods, I, x A, 61.
Bibliography, x A, 150.

BLACKMAR, F. W.

Penology in Kansas, i, 155.
Experiments in the Solution of the Labor Problem, iv, 15.
Productive Cooperation in England, vi B, 59.
Taxation in Kansas, part I, vi B, 171.
Economic and Social Influence of Irrigation, vii B, 27.
Taxation in Kansas part II, viii B, 19.

BROWN, BARNUM.

Two New Species of *Asilids* from New Mexico, vi A, 103.
Bibliography, viii A, 141.

CADY, H. P.

Chemical Analysis of Counterfeit Gold Dust (with V. L. Leighton), iii, 198.
A New Explosive Compound formed by the Action of Liquid Ammonia upon Iodine, vi A, 71.
The Detection of Arsenic, Antimony, and Tin, ix A, 259.
Bibliography, viii A, 142.

CANDY, A. L.

The Trisection of an Angle, I, ii, 35.
Bibliography, viii A, 142.

CANFIELD, A. G.

The Tone of Literature and the Writer's Responsibility, vii B, 39.

CARRUTH, W. H.

Foreign Settlements in Kansas, I, i, 71.
Dialect Word-list, I, i, 95.
Dialect Word-list, II, i, 157.
Foreign Settlements in Kansas, II, iii, 159.
Dialect Word-list, III, vi B, 51.
Pronouns Used in Address in Lessing's Dramas (with E. C. Alder), vi B, 65.
Dialect Word-list, IV (with Paul Wilkinson), vi B, 85.
Pronouns of Address in "The Idyls of the King," vi B, 159.

Digitized by Google

CASE, E. C.

Kansas Mosasaurs, I (with S. W. Williston), i, 15.
A Geological Reconnoissance in Southwest Kansas and No Man's Land, ii, 141.
Traces of a Glacier at Kansas City, Mo., iii, 149.
Bibliography, viii, A, 142.

CRANE, W. R.

A Curvimeter, iv, 121.
Horsebacks in the Kansas Coal Measures, iv, 145.
Bibliography, x A, 151.

DUNSTAN, A. St. C.

The Effect of Magnetism upon the Spectral Lines of Sodium (with M. E. Rice and C. A. Kraus), vi A, 78.
Note on the Yellow Helium Line (with M. E. Rice), viii A, 85.
Bibliography, viii A, 143.

EMCH, A.

A Special Class of Connected Surfaces, iii, 153.
Involutoric Transformations of the Straight Line, iv, 111.
Involutoric Collineations in the Plane and in Space, iv, 205.
Projective Groups of Perspective Collineations in the Plane Treated Synthetically, v, 1.
Theory of Compound Curves in Railroad Engineering, v, 99.
Bibliography, viii A, 144.

FRANKLIN, E. C.

A Chemical Examination of the Water of the Kaw and its Tributaries (with E. H. S. Bailey), iii, 91.
Bibliography, viii A, 145.
Bibliography, continued, x A, 152.

GILBERT, J. Z.

On the Skull of *Xerobates* (?) *undata* Cope, vii A, 143.

GOULD, C. N.

Stratigraphy of the McCann Sandstone, ix A, 175.

GOWELL, R. C.

The Myology of the Hind Leg of the Raccoon (*Procyon lotor*), vi A, 121.
Bibliography, viii A, 145.

GRIMSLEY, G. P.

Gypsum in Kansas, vi A, 16.

GROWE, Bessie E.

On New Canonical Forms of the Binary Quintic and Sextic, vi A, 201.
Bibliography, viii A, 145.

HARRIS, J. A.

Annotated Catalogue of the Crayfishes of Kansas, ix A, 263.
The Dimorphism of Cambarus, I, x A. 49.
Bibliography, x A, 152.

HAWORTH, E.

Report on Field Work in Geology (with M. Z. Kirk and W. H. H. Piatt), ii, 99.
The Stratigraphy of the New Coal Measures, iii, 271.
Division of the Kansas Coal Measures, iii, 291.
The Coal Fields of Kansas, iii, 297.

Digitized by Google

The Coffeyville Explosion, iv, 67.
Bibliography, viii A, 146.
Bibliography, continued, x A, 153.

HODDER, F. H.

Bibliography of Municipal Government in the United States, i, 179.
The Duty of the Scholar in Politics, v, 55.

HOLMES, D. H.

A Study of the Type of Greek Ephitaphos with Special Reference to the Oration in Thucydides, iv, 219.
The Limitations of the Composition of Verbs with Prepositions in Thucydides, v, 119.

HOPKINS, E. M.

The Character and Opinions of William Langland, ii, 233.
The Use of Analysis in Logical Composition, vi B, 1.
Notes on Brief-making, vi B, 127.
Notes on Piers Plowman, vii B, 1.

HOUGH, G. de N.

South American Muscidæ in the Collection of S. W. Williston, ix A, 203.

HUNTER, S. J.

Parasite Influence on *Melanoplus*, vii A, 205.
The Coccidæ of Kansas, I, viii A, 1.
The Coccidæ of Kansas, II, viii A, 67.
The Coccidæ of Kansas, III, ix A, 101.
The Coccidæ of Kansas, IV, x A.
Bibliography, viii A, 148.
Bibliography, continued, x A, 153.

HYDE, IDA H.

Collateral Circulation of the Cat after Ligation of the Postcava, ix A, 167.
Bibliography, viii A, 148.
Bibliography, continued, x A, 153.

IKENBERRY, L. D.

Experiments in Judging the Direction of Sound (with C. E. Shutt), vii A, 9.

KAHL, P. H. I.

Two New Species of Genera of Syrphidæ, *Mixogaster* Macq. and *Ceria* Fabr., vi A, 137.
Bibliography, viii A, 149.

KELLOGG, V. L.

Notes on *Melitera dentata* Grote, i, 39.
The Sclerites of the Head of *Danais archippus* Fabr., ii, 51.
The Taxonomic Value of the Scales of the Lepidoptera, iii, 45.
Bibliography, viii A, 149.

KIRK, M. Z.

Report of Field Work in Geology (with E. Haworth and W. H. H. Piatt), ii, 99.
The Sands of the Kansas River Valley, I, iv, 125.
Bibliography, x A, 153.

KRAUS, C. A.

The Effect of Magnetism upon the Spectrial Lines of Sodium (with A. St. C. Dunstan and M. E. Rice, vi A, 78.
Bibliography, x A, 153.

Digitized by Google

LANGE, WM.

On the Action of Sulphuric Acid upon Strychnine, in the Separation of this Alkaloid from Organic Matter (with E. H. S. Bailey), vi A, 205.
Bibliography, viii A, 150.

LEIGHTON, V. L.

Chemical Analysis of Counterfeit Gold Dust (with H. P. Cady), iii, 198.
Bibliography, x A, 154.

LOGAN, W. N.

The Temperature Sense, iii, 201.
Some New Cirriped Crustaceans from the Niobrara Cretaceous of Kansas, vi A, 187.
Some Additions to the Cretaceous Vertebrates of Kansas, viii, 87.
The Stratigraphy and Invertebrate Faunas of the Jurassic Formation in the Freeze-out Hills of Wyoming, ix A, 109.
Bibliography, viii A, 150.
Bibliography, continued, x A, 154.

LUCAS, F. A.

The Characters of *Bison occidentalis*, the Fossil Bison of Kansas and Alaska, viii A, 17.

MACOMB, J. N. JR.

Table for the Calculation of Analyses (with E. Bartow), vi A, 59.
Bibliography, viii A, 152.

MENKE, H. W.

Birds of Finney County, Kansas, iii, 119.
Bibliography, x A, 154.

MILLER, E.

Modern Higher Algebra, i, 133.
Bibliography, viii A, 152.
Bibliography, continued, x A, 154.

MOODY, A. E.

The Condition of Packing-house Employees, iv, 41.
Bibliography, x A, 154.

MURPHY, E. C.

Maximum Bending Moments for Moving Loads in a Parabolic Arch-rib Hinged at the Ends, i, 143.
Present Status of the Street-paving Problem in Kansas, ii, 27.
Maximum Load on a Lintel, ii, 31.
Irrigation in Western Kansas, iii, 117.
Collection and Storage of Waters in Kansas, iii, 217.
Notes on Air Resistance and Pressure, iv, 63.
The Theoretical and Measured Pumping Power of Windmills, iv, 93.
Notes on the Discharge of the Kansas River at Lawrence, Kan., since 1881, iv, 163.
Results of Windmill Tests, vi A, 89.
Power of a Twelve Foot "Power" Windmill, vi A, 191.
Bibliography, viii A, 153.

McCLUNG, C. E.

Refractive Index and Alcohol-solvent Power of a Number of Clearing and Mounting Media, vii A, 197.
The Spermatocyte Divisions of the Acrididæ, ix A, 73.
Bibliography, viii A, 151.
Bibliography, continued, x A, 154.

Digitized by Google

McFARLAND, D. F.

Action of Liquid Ammonia on Acid Chlorids and Esters (with E. Bartow), x A.
Bibliography, x A, 155.

NEWSON, H. B.

Unicursal Curves by Method of Inversion, i, 47.
Linear Geometry of the Cubic and Quartic, ii, 85.
The Hessian, Jacobian and Steinerian in the Geometry of one Dimension, iii, 103.
Continuous Groups of Projective Transformations Treated Synthetically, I, iv, 71.
Supplementary Note of the Article on Continuous Groups, iv, 169.
Continuous Groups of Projective Transformations Treated Synthetically, II, iv, 243.
Continuous Groups of Projective Transformations Treated Synthetically, III, v, 81.
Types of Projective Transformations in the Plane and Space, vi A, 63.
Normal Forms of Projective Transformations, vii A, 125.
The Five Types of Projective Transformations of the Plane, viii A, 43.
On the Construction of Collineations, ix A, 65.
On the Group of 216 Collineations in the Plane, x A, 13.
On the Group and Subgroups of Real Collineations Leaving a Tetrahedron Invariant (a New Theory of Collineations in Space, I), x A, 33.
A New Theory of Collineations in Space, II, x A, 87.
A New Theory of Collineations in Space, III, x A, 99.
Bibliography, viii A, 154.
Bibliography, continued, x A, 155.

PIATT, W. H. H.

Report of Field Work in Geology (with E. Haworth and M. Z. Kirk), ii, 99.
Bibliography, x A, 155.

PALMER, W. K.

The Designing of Cone Pulleys, vii A, 41.
The Hyperbolic Spiral, vii A, 155.
A Graphical Method of Constructing the Catenary, vii A, 210.
Bibliography, viii A, 155.

PALMER, C. F.

Salicylic Acid and Calcium Sulfite as Preservatives of Cider (with E. H. S. Bailey , vi A, 111.
Bibliography, viii A, 156.

PROSSER, C. S.

The Permian and Upper Carboniferous of Southern Kansas, vi A, 149.
Note on the Distribution of Cheyenne Sandstone, viii A, 135.
Bibliography, x A, 155.

RICE, M. E.

The Effect of Magnetism upon the Spectral Lines of Sodium (with A. St. C. Dunstan and C. A. Kraus), vi A, 78.
Alternating Currents in Wheatstone's Bridge, vii A, 31.
Note on the Yellow Helium Line (with A. St. C. Dunstan), viii A, 85.
Bibliography, viii A, 157.

RIGGS, E. S.

A New Species of *Dinictis* from the White River Miocene of Wyoming, iv, 237.
Hoplophoneus occidentalis, v, 37.
Bibliography, viii A, 157.

Digitized by Google

RIGGS, H. C.

On Pascal's Limacon and the Cardioid, i, 89.
Bibliography, viii A, 157.

ROGERS, A. F.

Cuprogoslarite—a New Variety of Zinc Sulphate, viii A, 105.
New and Little Known Pelecypods from the Coal Measures (with J. W. Beede), viii A, 131.
Normal Ankerite from Phelps County, Missouri, viii A, 183.
A New Genus and Species of Bryozoans from the Coal Measures of Kansas and Missouri, ix A, 1.
Annotated list of Minerals Occurring in the Joplin Lead and Zinc District, ix A, 161.
Occurrence of the Bryozoan Genus *Rhabdomeson* in America, ix A, 173.
Coal Measure Faunal Studies, I (with J. W. Beede), ix A, 233.
Bibliography, viii A, 157.
Bibliography, continued, x, A 156.

ROUSE, J. E.

The Visual Perception of Distance, v A, 109.
Bibliography, x A, 156.

SELLARDS, E. H.

Notes on the Permian Flora of Kansas, ix A, 63.
A New Genus of Ferns from the Permian of Kansas, ix A, 179.
Permian Plants—*Tæniopteris* of the Permian in Kansas, x A, 1.
Bibliography, x A, 157.

SHUTT, C. E.

Experiments in Judging the Distance of Sound, vii A, 1.
Experiments in Judging the Distance of Sounds (with L. D. Ikenberry), vii A, 9.

SNOW, MARTHA B.

The Servant-girl Problem, iv, 31.
Bibliography, x A, 158.

SNOW, W. A.

Notes and Descriptions of Syrphidæ, i, 33.
Descriptions of North American Trypetidæ, with Notes, part I, ii, 159.
American Platypezidæ, I, iii, 143.
Cnephalia and its Allies, iii, 177.
A New Species of *Pelecocera*, iii, 187.
American Platypezidæ, II, iii, 205.
Diptera of Colorado and New Mexico, iii, 225.
Supplementary List of North American Syrphidæ, iii, 249.
On *Toxotrypana* of Gerstaecker, iv, 117.
List of Asilidæ, Supplementary to Osten Sacken's Catalogue of North American Diptera, 1878–'95, iv, 173.
Bibliography, viii A, 167.

STEVENS, W. C.

Notes on Some Diseases of Grass, i, 123.
On the Behavior of Kinoplasm and Nucleolus in the Division of the Pollen Mother Cells of *Asclepias cornuti*, vii A, 77.
Apparatus to Facilitate the Process of Fixing and Hardening Material, vii A, 107.
Bibliography, viii A, 167.

Digitized by Google

STEWART, ALBAN.

A Geological Section at Providence, Mo., iv, 161.
Restoration of *Oreodon culbertsonii* Leidy, vi A, 13.
Notes on the Osteology of *Bison antiquus* Leidy, vi A, 127.
A Contribution to the Ichthyic Fauna of the Kansas Cretaceous, vii A, 21.
Individual Variations of the Genus *Xiphactinus* Leidy, vii A, 115.
Some Notes on the Genus *Saurodon* and Allied Species, vii A, 177.
A Preliminary Description of Seven New Species of Fish from the Cretaceous of Kansas, viii A, 37.
A Preliminary Description of the Opercular and other Cranial Bones of *Xiphactinus* Leidy, viii A, 19.
Pachyrhizodus minimus, a New Species of Fish from the Cretaceous of Kansas, viii A, 37.
Notice of Three New Cretaceous Fishes, with Remarks on the Saurodontidæ Cope, viii A, 107.
Notes on the Osteology of *Anogmius polymicrodus* Stewart, viii A, 117.
Bibliography, viii A, 168.

SWEM, E. G.

A Preliminary Report on the Glaciated Area of Kansas, iv, 153.

SUTTON, W. B.

The Spermatogonial Divisions in *Brachystola magna*, ix A, 135.
Bibliography, x A, 158.

TEMPLIN, O.

The Duty of the State to the Scholar, vi B, 87.

WAGNER, G.

On Some Turtle Remains from the Fort Pierre, vii A, 201.
On *Tetracaulodon shepardii* Cope, viii A, 99.
Bibliography, viii A, 169.

WALKER, A. T.

The Sequence of Tenses in Latin, vii B, 57.

WARD, FRANK E.

A Plan for Increasing the Capacity of the Heating Plant of Spooner Library, University of Kansas, vii A, 149.

WELLMAN, MARY H.

The Prothorax of Butterflies, iii, 137.
Bibliography, viii A, 169.

WILKINSON, P.

Dialect Word-list, IV (with W. H. Carruth), vi B, 85.

WILLISTON, S. W.

Kansas Pterodactyls, I, i, 1.
Kansas Mosasaurs, I (with E. C. Case), i, 15.
Diptera brasiliana, II, i, 43.
On the Apioceridæ and their Allies, i, 101.
Diptera brasiliana, III, i, 110.
New or Little-known Diptera, ii, 59.
Kansas Pterodactyls, II, ii, 79.
Kansas Mosasaurs, II, ii, 83.
Restoration of a Rhinoceros (*Aceratherium fossiger*), ii, 289.

Digitized by Google

Vertebrate Remains from the Lowermost Cretaceous, iii, 1.
A New Turtle from the Benton Cretaceous, iii, 5.
Notes on *Uintacrinus socialis* Grinnell, iii, 19.
Restoration of *Platygonus*, iii, 23.
The Genus *Dolichomyia*. with Description of a New Species, iii, 41.
New or Little-known Extinct Vertebrates, iii, 165.
Exotic Tabanidæ, iii, 189.
Semi-arid Kansas, iii, 209.
Dialysis and *Triptotricha*, iii, 263.
New Bombylidæ, iii, 267.
Notes on the Mandible of *Ornithostoma*, iv, 61.
Two Remarkable Genera of Diptera, iv, 107.
Bibliography of North American Dipterology, 1878–'95, iv, 129.
Fissicorn Tachinidæ, iv, 171.
On the Skull of *Ornithostoma*, iv, 195.
Bibliography of North American Dipterology, II, iv, 199.
On the Dermal Covering of *Hesperornis*, v, 53.
Diptera brasiliana, IV, vi A, 1.
Restoration of *Ornithostoma* (*Pteranodon*), vi A, 35.
Notice of Some Vertebrate Remains from the Kansas Permian, vi A, 57.
Brachysaurus, a New Genus of *Pythonomorpha*, vi A, 96.
On the Extremities of *Tylosaurus*, vi A, 97.
Restoration of Kansas Mosasaurs. vi A, 107.
Range and Distribution of Mosasaurs, with Remarks on Synonymy, vi A, 177.
A New Labyrinthodont from the Kansas Carboniferous, vi A, 209.
The Sacrum of *Morosaurus*, vii A, 173.
Some Prehistoric Ruins in Scott County, Kansas, vii B, 109.
Some Additional Characters of the Mosasaurs, viii A, 39.
A New Genus of Fishes from the Niobrara Cretaceous, viii A, 113.
A New Species of *Sagenodus* from the Kansas Coal Measures, viii A, 175.
Notes on the Coraco-scapula of *Eryops* Cope, viii A, 185.
Some Fish Teeth from the Kansas Cretaceous, ix A, 27.
Bibliography viii A, 169.
Bibliography, continued, x A, 158.

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GENERAL INDEX TO VOLUMES I TO X OF THE KANSAS UNIVERSITY QUARTERLY.

A.

A new genus of ferns from the Permian of Kansas, ix,* 179.
A reconnaissance in the Blue Valley Permian, ix, 191.
Accessory chromosome in Scolopendra, x, 71.
Aceratherium fossiger, ii, 289.
  restoration of, ii, 290.
Acid chlorids, action with anhydrous ammonia, x, 89.
Acima, ii, 165.
Acrididæ, the spermatocyte divisions of the, ix, 73.
Acroglossa hesperidarum, iii, 184.
Actias luna, ii, 52.
  clypeus of, ii, 52.
  genæ of, ii, 52.
  epicranium of, ii, 53.
  occiput of, ii, 53.
Adulteration of buckwheat flour, vii, 37.
Africa, 1875, European possessions in, viii B, map I.
  1884, European possessions in, viii B, map II.
  1885, European possessions in, viii B, map III.
  1899, European possessions in, viii B, map IV.
  The partition of, viii B, 1.
Agnotomyia, iii, 265.
Air resistance and pressure, notes on, iv, 63.
Alcohol-solvent power of clearing and mounting media, vii, 197.
Alethopteris, systematic description of, x, 7.
Algæ, apparatus for the study of, vii, 112.
Allograpta obliqua, i, 37.
Allograpta obliqua, iii, 239.
Allotrichoma abdominale, vii, 4.
Alternating currents in Wheatstone's bridge, vii, 31.
American cities, government of, bibliography, i, 124.
American Dialect Society, i, 73, 137.
American Indians, temperature sense in, iii, 203.
American Naturalist, ii, 156.
Amids, formation of, by anhydrous ammonia, x, 79.
Ammonia, anhydrous action of, on acid chlorids, x, 80.
  on esters, x, 81.
  liquid, explosive compound formed by the action of, upon iodine, vi, 71.
Amplexus westii, vii, 17.
Analysis, rocks of Great Spirit spring, i, 85.
Analyses, table for the calculation of, vi, 50.
Androconia of Lepidoptera, iii, 76.
  of Argynnis idalia, Danais archippus, Dichronia, Hadena, iii, 78.
  of Papilio, Pieris rapæ, iii, 77.
  of Sphinx ligastri, Thecla calamus, iii, 78.
Andropogon furcatus, i, 123.
Androstomus vociferus, iii, 133.
Ankerite from Phelps county, Missouri, by Austin F. Rogers, viii, 183.
Annotated catalogue of the crayfishes of Kansas, ix, 263.
Annotated list of the minerals occurring in the Joplin lead and zinc district, ix, 161.
Anogmius polymicrodus Stewart, notes on the osteology of, viii, 117.
Anomia, ii, 165.
Antimony, and tin, the detection of arsenic, ix, 259.
Apical point in spermatocytes of Scolopendra, x, 66, 67.
Aptorthus, ii, 48.
  albicillatus, ii, 48.
  borealis, ii, 49.
  nigripes, ii, 49, 50.
  townsendi, ii, 50.
Arctophila flagrans, iii, 242.
Argynnis cybele, ii, 52.
  clypeus of, ii, 52.
Argyromœba, iii, 43.
Arsenic, antimony, and tin, the detection of, ix, 259.
  microscopic comparison of samples of white, ix, 255.
Arthrostylum fascipennis, n. sp., iv, 109.
Arthrostylium, gen. nov. (Leptidæ), iv, 108.
Apiocera, i, 110.
  brevicornis, i, 102.
Apioceridæ, i, 101.
  literature of, i, 116.
Apparatus to facilitate the process of fixing and hardening material, vii, 107.
Asclepias cornuti, vii, 77.
Asilidæ, mouth parts of, i, 114.
  a list of, supplementary to Osten Sacken's Catalogue of North American Diptera, 1878-'95, iv, 173.
  bibliography of, iv, 189.
Asilids, new species of, vi, 103.
Asilus affinis, ii, 73.
  angustifrons, ii, 71.

* Unless otherwise indicated, references are to "Series A."

Digitized by Google

Asilus annulatus, ii, 70.
arizonensis, ii, 76.
astutus, ii, 70.
callidus, ii, 75.
distinctus, ii, 73.
flavipes, ii, 72.
leucopogon, ii, 75.
midas, ii, 69.
notatus, ii, 74.
novæ scotiæ, ii, 68.
sericus, ii, 68.
Aspidiotus æsculi, subspecies solus, sub. sp. n., viii, 12.
ancyclus, viii, 4.
fernaldi, subspecies albiventer, sub. sp. n., viii, 6.
forbesi, viii, 3.
greenii, viii, 11.
herderæ, viii, 11.
juglans-regiæ, viii, 8.
obscurus, viii, 7.
osborni, viii, 5.
perniciosus, viii, 10.
ulmi, viii, 6.
uvæ, viii, 4.
Astacus, spring and autumn ecdyses of, x, 53.
Asteronella, i, 87.
Auburn, penitentiary at, i, 161.
Aulopora? anna, vii, 18.
prosseri, vii, 18.
Austen, E. E., iii, 264.
Avena sativa, i, 126.
Axial filament, origin of, in Scolopendra, x, 70 and 74.

B.

Baccha clavata, iii, 239.
lemur, iii, 240.
obscuricornis, iii, 240.
Bacteria, relation of, to oxygen, vii, 111.
Basal points of a system of cubics, i, 52, 56.
Basal points of a system of quartics, i, 66, 69.
Baur, Geo., classification of Mosasauridæ, i, 15.
Beckeriella, vi, 2.
bispinosa, vi, 2.
Belvosia, iii, 181.
Berkeley, visual theory of, v, 109.
Berlin, municipal government of, bibliography, i, 183.
Bertillon system of registry of criminals, i, 173.
Beryx?, vii, 195.
Beryx multidentatus, vii, 196.
polymicrodus, vii, 195.
Bibliography of North American diptera, 1878–'95, iv, 129.
Bibliography, a brief, of municipal government in the United States, i, 179.
Bibliography of scientific publications by members of the University of Kanas, viii, 138.
Bigot, J. F. M., ii, 28, 47, 48.
Binocular perception of space, v, 112, 117.
Biographical statistics of reformatory inmates, i, 166.
Blepharoceridæ, a new genus of, i, 119.
Bison antiquus, notes on the osteology of, vi A, 127.
latifrons, vi, 127.
the fossil, of Kansas and Alaska, viii, 17.
occidentalis, the character of, viii, 17.
Blepharoneura, ii, 167.
Blue Valley Permian, a reconnaissance in the, ix, 191.
Bohemians in Kansas, iii, 159, 161.
Bombyliidæ, new, iii, 267.
Booth, Charles, investigations of, i, 164.
Bos americanus, comparison of, v, 129.
Boston, municipal government of, bibliography, i, 195.
Bouteloua racemosa, i, 123.
Brachyopa cynops, iii, 240.
vacua, iii, 246.
Brachydeutra argentata, vi, 4.
Brachypalpus parvus, iii, 247.
dimidiata, vi, 4.
Brachysaurus, vi, 96.
overtoni, vi, 96.
a new genus of Mosasaurs, vi, 95.
Brachystola magna, the spermatogonial divisions of, ix, 135.
Brauer, Dr. F. M., vii, 209.
Bryozoans from the Coal Measures of Kansas and Missouri, new, ix, 1.
Bryozoan genus Rhabdomeson in America, occurrence of, ix, 173.
Brefeld, experiments of, i, 127.
Brockway, Z. R., superintendent Elmira reformatory, i, 165, 166.
Buckwheat flour, adulteration of, vii, 37.
Budget, control of the, in the United States government, ii, 175.
effect of the English on the American, ii, 213.
Burgess, Edward, cited, ii, 52, 55, 56.
Burlington limestone, iii, 277, 281; vii, 232.
named, ii, 110.
Burmeister, H., cited, ii, 54.
Butterflies, a study of the prothorax of, iii, 137.

C.

Calculation of analyses, table for, vi A, 111.
Caley's method for unicursal quartics, i, 58.
Callicera, iii, 187.
generic characters of, i, 33.
mentensis, iii, 225.
montensis, i, 34.
Callomyia, iii, 143, 151.
amœna, iii, 144, 152.
aurantiaca, iii, 207.
bella, iii, 145, 151.
divergens, iii, 151.
humeralis, iii, 207.
leptiformis, iii, 144, 152.
notata, iii, 151.
talpula, iii, 151.
tenera, iii, 151.
torporata, iii, 151.
venusta, iii, 144, 151, 207.
Calotarsa, iii, 143.

Digitized by Google

Cambarus, dimorphism of, x, 49, 59.
immunis, characters of first and second form males, x, 50, 53.
preparation of material from, x, 54.
summary of results upon, x, 59.
table showing condition of specimens, x, 55, 58.
Campophyllum torquium Owen, notes on, vii, 187.
Canadian Entomologist, i, 39.
Canadian Naturalist, i, 41.
Canonical forms of binary quintic and sextic, vi A, 201.
Canonical forms of projective transformations, vii, 132, 140.
Carboniferous of Kansas, iii, 216.
two new crinoids from the Kansas, ix, 21.
Cardioid, articles on the, i, 89.
as a cuspidal quartic, i, 63.
Carlyle limestone, iii, 277.
named, ii, 110.
Carphotricha culta, ii, 169.
Catabomba pyrastri, iii, 232.
Cat, collateral circulation in the, ix, 167.
Catalogue of the crayfishes of Kansas, annotated, ix, 263.
Catenary, analytical properties of, vii, 214.
center of gravity of, graphically, vii, 218.
conforming to given conditions, vii, 222.
equation of deduced, vii, 212.
formed by given length of cord, vii, 222.
four cases of the, vii, 222.
generated by rolling parabola, vii, 217.
graphical method for constructing, vii, 211.
graphical representation of properties of, vii, 212.
sum of two exponential curves, vii, 218.
through given points, vii, 222.
to plot the, vii, 218.
Catocala, sp., ii, 54.
gula of, ii, 54.
labium of, ii, 57.
maxillary palpi of, ii, 56.
Caucasians, temperature sense in, iii, 202.
Celloidin-paraffin, method of embedding, x, 62.
Ceratitis, ii, 165.
Ceria, iii, 187.
abbreviata, townsendi, tridens, iii, 246.
preoccupied, vi, 146.
signifera Loew, vi, 144.
willistoni, n. sp., vi, 141.
willistoni, synonyms of, vi, 144.
Ceriocrinus monticulatus, n. sp., viii, 123.
Character of Bison occidentalis, the fossil bison of Kansas and Alaska, viii, 17.
Characteristics of Coal Measure limestone, iii, 280.
Charadrius squatarola, iii, 132.
Chanute shales, named, ii, 109.
Charleston, municipal government of, bibliography, i, 196.
Cheyenne sandstone, note on the distribution of, by Charles S. Prosser, viii, 135.
Cherokee shales, iii, 272.
coal beds of, iii, 305.
deposition of, iii, 285.
extent of, iii, 272.
faults in, iii, 284.
named, ii, 105.
Cherry Hill prison, i, 160.
Chicago, municipal government of, bibliography, i, 196.
Chilosia chalybescens, ii, 76.
comosa, iii, 247.
lasiophthalma, iii, 247.
lucta, iii, 228.
lugubris, iii, 227.
petulca, iii, 228.
sororcula, iii, 228.
sp., iii, 229.
tarda, iii, 228.
willistoni, iii, 227.
Chrysochlamys crœsus, iii, 245.
Chrysogaster bellula, nigrovittata, iii, 227.
Chrysops intrudens, iii, 191.
varians, iii, 192.
Chrysotoxum derivatum, i, 34; iii, 226.
integrum, iii, 227.
ypsilon, iii, 226.
Church service in a foreign tongue in Kansas, iii, 162.
Cimoliasaurus, iii, 2.
Cirriped crustaceans from the Niobrara Cretaceous of Kansas, vi, 187.
Cissoid of Diocles, properties of, i, 50, 51, 70.
Cladochonus benetti, vii, 17.
Class demonstration material of cryptogamic plants, vii, 111.
Claviceps, diseased ovaries of, i, 123.
Claviceps purpurea, i, 123, 130.
effect of, i, 131.
hosts of, i, 131.
Clearing media, refractive index and alcohol-solvent power of, vii, 197.
Clepsydrops, vi A, 55.
Clidastes, i, 16; iii, 167; vi, 101.
species of, i, 17.
tortor, ii, 84.
velox, description of, i, 17; ii, 83.
westii, description of, i, 29.
Cnephalia, iii, 177.
americana, iii, 182.
bisetosa, iii, 178.
hebes, iii, 177.
multisetosa, iii, 178.
pansa, iii, 182.
ruficauda, iii, 183.
Cnephaliodes, iii, 186.
Coal in Kansas, areal extent of, iii, 297.
chemical properties of, iii, 306.
commercial value of, iii, 307.
counties producing, iii, 297.
geologic position of, iii, 300.
physical properties of, iii, 305.
production of, iii, 308.
stratigraphy of, iii, 305.
Coal Measures, division of, iii, 291.

Digitized by Google

Coal Measures, characteristics of limestones of, iii, 280.
characteristics of sandstones of, iii, 282.
extent of marginal areas of, iii, 283.
faunal studies, ix, 233.
general conditions of disposition of, iii, 286.
of Kansas and Missouri, new Bryozoans from, ix, 1.
ratio of components of, iii, 279.
stratigraphy of, iii, 271.
sandstone, iii, 282.
a new species of Sagenodus from the Kansas, viii, 175.
new and little known Pelecypods from, viii, 131.
new fossils from the Kansas, viii, 123.
of Kansas, new forms of Pseudomonotis from, viii, 79.
Coal-mining, probable future of, in Kansas, iii, 309.
Coal oil and gas in Kansas, iv, 1.
Coccidæ of Kansas, I, viii, 1; II, viii, 67; III, ix, 101; IV, x, 107.
Coffeyville explosion, iv, 67.
Colias cæsonia, prothorax of, iii, 139.
Collateral circulation in the cat after ligation of the postcava, ix, 167.
Collection and storage of water in Kansas, iii, 217.
Collineations in the plane, projective groups of perspective, v, 1.
in the plane, group of 216, x, 13, 16.
involutoric, in the plane and in space, iv, 205.
on the construction of, ix, 65.
Colorado Cretaceous of Kansas, iii, 216.
Columbus sandstones, named, ii, 106.
Comanche Cretaceous, iii, 1.
of Kansas, iii, 216.
Composition of verbs with prepositions in Thucydides, v, 119.
Compound curves in projective transformations, v, 99.
Comstock, Prof. J. H., cited, ii, 53.
quoted, iii, 45, 60, 61, 83.
Cone pulleys, comparison of methods for designing, vii, 45.
complete solution for problem of proportioning, vii, 56.
designing of, vii, 41.
for crossed belts, vii, 57.
for open belts, vii, 53.
new graphical treatment of, vii, 53.
the problem of proportioning, vii, 42.
Reuleaux analysis for, vii, 47.
rules for proportioning the steps of, vii, 63.
Confervæ, i, 87.
Connected surfaces, a special class of, iii, 153.
Conops angustifrons, i, 44.
grandis, i, 44.
inornatus, i, 45.
magnus, i, 43.
nobilis, i, 45.
Conops ornatus, i, 46.
parvus, i, 46.
rufus, 1, 44.
Constitution, interpretation of provisions on origination of money bills, ii, 182.
debates in first Congress, ii, 182.
from 1792 to 1800, ii, 185.
in twenty-second Congress, ii, 187.
in twenty-fifth Congress, ii, 191.
in twenty-eighth Congress, ii, 192.
in thirty-fourth Congress, ii, 194.
in thirty-fifth Congress, ii, 198.
in forty-first Congress, ii, 201.
in forty-second Congress, ii, 204.
in forty-sixth Congress, ii, 208.
from 1881 to 1891, ii, 209.
Construction of collineations, on the, ix, 65.
Continuous groups, supplementary notes to the article on, iv, 169.
Contribution to the knowledge of the ichthyic fauna of the Kansas Cretaceous, vii, 21.
Copestylum marginatum, i, 37, 41; iii, 241.
Coraco-scapula of Eryops Cope, notes on the, viii, 185.
Corals, new, from the Kansas Carboniferous, vii, 17.
Corbula, sp., viii, 92.
Corn, number of parasites of, i, 223.
Cossidæ, scales of, iii, 86, 87.
Cottonwood Falls limestone, iii, 279, 283, 284.
Counterfeit gold dust, chemical analysis of, iii, 197.
Covariants of the cubic, ii, 88.
Cragin, F. W., vii, 123.
Crayfishes of Kansas, annotated catalogue of the, ix, 263.
Cretaceous, some fish teeth from the Kansas, ix, 27.
a new turtle from the Benton, iii, 5.
fishes, new species of, vii, 21, 117, 191.
fishes, notice of three new, with remarks on the Saurodontidæ Cope, viii, 107.
invertebrates of Kansas, some additions to, viii, 87.
new genus of fishes from the Niobrara, viii, 13.
of Kansas, Pachyrhizodus minimus, a new species of fish from, viii, 37.
vertebrate remains from the lowermost, iii, 1.
Cricotus, vi A, 253.
Crinoids from the Kansas Carboniferous, two new, ix, 21.
Crioprora cyanogaster, iii, 247.
Criorrhina umbratilis, i, 38.
Critic centers of a system of quartics, i, 66, 68.
Crocodilia, iii, 3.
Cryptogamic plant material, vii, 111.
Ctenophora angustipennis, similis, ii, 63.
Cubics, basal points of a system of, i, 52, 56.
critic centers of a system of, i, 52, 53.
cuspidal, i, 50, 51.
nodal, i, 49, 50.
Cubics through nine points, pencil of, x, 13.

Digitized by Google

Cuprogoslarite, a new variety of zinc sulphate, viii, 105.
Curupira, vi, 12.
Curvimeter, a, iv, 121.
Cyanocephalus cyanocephalus, iii, 133.
Cyrtopogon dasyllis, ii, 66.

D.

Dactylomyia, ii, 151.
gracilipes, ii, 151.
Dakota Cretaceous of Kansas, iii, 216.
Dasyis archippus, ii, 51.
clypeus of, ii, 51.
dorsal aspect of prothorax of, iii, 137.
epicranium of, ii, 53.
epipharynx of, ii, 56.
fixed parts of the head of, ii, 57.
genæ of, ii, 52.
gula of, ii, 54.
labial palpi of, ii, 57.
labium of, ii, 57.
labrum of, ii, 54.
mandibles of, ii, 53, 56.
maxillæ of, ii, 56.
movable parts of the head of, ii, 53.
occiput of, ii, 53.
pilifers of, ii, 55.
post-genæ of, ii, 53.
sclerites of the head of, ii, 51.
tentorium of, ii, 54.
Daptinus, vii, 22.
broadheadii, vii, 24.
Degenerate cubics of pencil through nine points, x, 14.
Density of population dependent upon abundance of food-supply, vii B, 27.
Dermal covering of Hesperornis, v, 53.
Designing of cone pulleys, vii, 41.
Desmatochelyidæ, iii, 5.
Desmatochelys, iii, 5.
lowii, iii, 5.
Desmatoneura, iii, 267.
argentifrons, iii, 267.
Desmatomyia, iii, 268.
anomala, iii, 268.
Detection of arsenic, antimony, and tin, ix, 259.
Diachlorus curvipes, iii, 193.
Dialect study, a contribution to, i, 71.
word-list, i, 95, 137.
Dialysis, iii, 265.
aldrichi, iii, 265.
dissimilis, iii, 263.
elongata, iii, 265.
rufithorax, iii, 265.
Dialysis and Triptotricha, iii, 263.
Diaspis snowii, n. sp., viii, 14.
Dichelacera scutellata, iii, 193.
Didea fuscipes, iii, 238.
laxa, iii, 238.
Diniotis, sp., iii, 173.
a new secies of, from the White River Miocene of Wyoming, iv, 237.
paucidens Riggs, iv, 239.
Dinotomius atrox, iii, 170.
Direction of sound, experiments in judging, vii, 9.
Distance of sound, experiments in judging, vii, 1.
Dipalta, iii, 43.
Diphtheria in Kansas, viii, 23.
map showing distribution of, by counties, viii, 33.
Diptera of Colorado and New Mexico, iii, 225.
Diptera, bibliography of North American, iv, 199.
brasiliana, i, 43, 119.
brasiliana, part IV, vi, 1.
list of Asilidæ, iv, 173.
new or little-known, ii, 59.
two remarkable new genera of, iv, 107.
Discharge of the Kansas river at Lawrence, Kan., since 1881, iv, 163.
Dissosteira longipennis, i, 39.
Distance, visual perception of, v, 109.
Distribution of the Mosasaurs, vi A, 177.
Dolichopodidæ, ii, 147.
new genera and species of, ii, 151.
Dolichopus and Hygroceleuthus, revision of the genera, ii, 1.
additions to revision of, ii, 154.
Dolichopus, ii, 1, 2, 23, 152.
table of species, ii, 2.
acuminatus, ii, 2.
agilis, ii, 5, 16, 26.
albicilliatus, ii, 3, 9.
albicoxa, ii, 3, 10.
angustatus, ii, 5, 15.
aurifacies, ii, 6, 20.
batillifer, ii, 4.
bifractus, ii, 4, 12.
brevimanus, ii, 3, 10.
brevipennis, ii, 3, 10.
brunneus, ii, 5, 14.
calcaratus, ii, 2, 8.
canaliculatus, ii, 6.
coloradensis, ii, 26.
comatus, ii, 5, 14.
convergens, ii, 2, 9.
coquilletti, ii, 6, 19.
corax, ii, 2, 7.
cuprinus, ii, 4, 7, 12.
dakotensis, ii, 4, 11.
detersus, ii, 2, 8.
discifir, ii, 5.
dorycerus, ii, 3.
duplicatus, ii, 6, 18, 157.
endactylus, ii, 4, 11.
flagellitenens, ii, 1, 4, 13.
fulvipes, ii, 5.
funditor, ii, 6, 20.
germanus, ii, 1, 6, 21.
gracilis, ii, 5, 15.
grandis, ii, 6, 21, 156.
gratus, ii, 2, 7, 8.
hastatus, ii, 4, 13.
henshawi, ii, 1, 4.
incisuralis, ii, 5, 14.

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Dolichopus incongruus, ii, 1, 3.
johnsoni, ii, 2, 7.
kansensis, ii, 2, 8.
laticornis, ii, 2, 7.
lobatus, ii, 5, 16.
longimanus, ii, 3, 10.
longipennis, ii, 4, 6, 12, 13.
luteipennis, ii, 4.
marginatus, ii, 5, 17.
melanocerus, ii, 5.
myosota, ii, 2.
nudus, ii, 3.
obcordatus, ii, 4, 5, 14.
occidentalis, ii, 6, 19.
ovatus, ii, 2, 9, 156.
pachycnemus, ii, 3, 9.
palæstricus, ii, 3, 10.
platyprosopus, ii, 5.
plumipes, ii, 4, 13.
plumosus, ii, 6, 18, 19.
pollex, ii, 5.
præustus, ii, 5.
pugil, ii, 5.
pulchrimanus, ii, 23.
quadrilamellatus, ii, 6.
ramifer, ii, 4, 12, 157.
reflectus, ii, 4, 12.
ruficornis, ii, 6.
sarotes, ii, 6.
scapularis, ii, 6, 20, 23.
scoparius, ii, 6, 18.
setifer, ii, 2, 156.
setosus, ii, 5, 14.
sexarticulatus, ii, 6.
socius, ii, 3, 10.
splendidulus, ii, 3.
splendidus, ii, 3, 11,
subciliatus, ii, 4.
tener, ii, 4.
tenuipes, ii, 155.
terminalis, ii, 6.
tetricus, ii, 2.
tonsus, ii, 4.
variabilis, ii, 4, 11.
vigilans, ii, 5, 13.
vittatus, ii, 4, 6, 12.
willistonii, ii, 6, 22.
xanthocnemus, ii, 3, 9.
Dolichomyia, iii, 41.
gracilis, iii, 41.
Douglas formations along the Kansas river, the Pottawatomie and, ix, 234.
Drosophila opaca, vi, 12.
Dutch settlements in Kansas, iii, 162.

E.

Eacles imperialis, i, 39.
Eclimus sodalis, ii, 65.
auratus, ii, 66.
lotus, ii, 66.
melanosus, ii, 65.
muricatus, ii, 65.
Economic and social influences of irrigation, vii B, 27.
Economic Fungi, Seymour and Earle's, i, 129.
Edestosaurus, synonymy of, i, 26.
Effect of irrigation on prices, vii B, 33.
Elephas, vii, 124.
Elmira reformatory, i, 165, 169, 176, 177.
Elymus canadensis, i, 123.
virginicus, i, 123.
Empis sociabilis, ii, 66.
Employees, the condition of packing-house, iv, 41.
Empo lisbonensis, n. sp., viii, 111.
Enchodus amicrodus, vii, 193.
parvus, vii, 192.
Entomological News, i, 41.
Ephydra bispinosa, vi, 2.
Epibates muricatus, ii, 65.
Epitaphios, a study of the type of the Greek, iv, 219.
Epochra canadensis, ii, 159.
Equianharmonic cubics of pencil through nine points, x, 14.
Equisetum, method of demonstrating distribution of spores, viii, 113.
Erie limestone, named, ii, 108.
Erie limestone, iii, 275, 280.
Eriophorum virginicum, i, 124.
Eriocera obscura, ii, 61.
eriophora, ii, 61.
Erisichthe, vii, 22.
Erisocrinus megalobrachius, n. sp., viii, 124.
Eristalis brousi, i, 38.
brousi, iii, 243.
flavipes, iii, 243.
hirtus, iii, 242.
latifrons, i, 38; iii, 242.
scutellaris, iii, 247.
tenax, iii, 242.
transversus, iii, 243.
Eryops Cope, notes on the coraco-scapula of, viii, 185.
Erysiphe graminis, hosts of, i, 131.
Escarpment, Altamont, vii, 95.
Burlington, vii, 99.
Burlington, vii, 232.
Carlyle, vii, 97.
Earlton, vii, 96.
Elk Falls, vii, 99.
Erie, vii, 95.
Eureka, vii, 100.
Hertha, vii, 95.
Howard, vii, 100.
Independence, vii, 96.
Iola, vii, 96.
Mound Valley, vii, 96.
Oswego, vii, 94.
Pawnee, vii, 94.
Reece, vii, 101.
Essential Parameters of projective tranformations, vii, 125, 126.
Ethiopians, temperature sense in, iii, 203.
Eupeodes volucris, i, 36; iii, 232.
Euchoerus macrops, iii, 24.
Eucnephalia, iii, 180, 185.
gonioides, iii, 185.

Digitized by Google

Eudamus, prothorax of, iii, 145.
tityrus, iii, 141.
Euræsta æqualis, ii, 171.
bella, ii, 171.
bellula, ii, 172.
festina, ii, 171.
mexicana, ii, 172.
European cities, government of, bibliography, i, 181.
Eurosta comma, ii, 169, 170.
fenestrata, ii, 169.
latifrons, ii, 161.
reticulata, ii, 170, 171.
solidaginis, ii, 169, 170.
Eutreta diana, ii, 158.
diana, var., ii, 158.
longicornis, ii, 158.
sparsa, ii, 167.
Evaporation in the arid region, iii, 118, 211.
Explosive compound, formed by the action of liquid ammonia upon iodine, vi A, 71.
Explosion, the Coffeyville, iv, 67.
Exponential curve, construction for, vii, 220.
use of, in plotting the catenary, vii, 218.
Extremities of Tylosaurus, vi A, 99.
Extinct vertebrates, new or little known, iii, 165.

F.

Family of surfaces invariant under hG_2(ABCl) of type II, x, 89.
Faunal studies, Coal Measures, ix, 233.
Felis maxima, iii, 174.
Ferns from the Permian of Kansas, a new genus of, ix, 179.
method of demonstrating distribution of spores, vii, 113.
Finance committees, development of, in the house of representatives, ii, 217.
in the senate, ii, 220.
Finance of American cities, bibliography, i, 186.
Finney county, Kansas, bird fauna of, iii, 129.
causes affecting abundance of bird fauna of, iii, 129.
topography of, iii, 129.
list of birds, iii, 129.
Fish teeth from the Kansas Cretaceous, some, ix, 27.
Fish, a new species of, from the Cretaceous of Kansas, viii, 37.
Fishes, a new genus of, from the Niobrara Cretaceous, viii, 113.
Cretaceous, iii, 2; vii, 21, 115, 177, 191.
three new Cretaceous, viii, 107.
Fissicorn Tachinidæ, iv, 171.
Fissures and faults, iii, 284.
Five-parameter subgroups of G_6 (Apl) of type V, x, 100, 104.
Fixing and hardening material, apparatus to facilitate the process of, vii, 107.
Food-supply, density of population dependent upon, vii B, 27.
progress and activity of society dependent upon, vii B, 28.
Foreign settlements in Kansas, i, 71; iii, 159.
Fort Pierre Cretaceous, iii, 216.
turtle remains from, vii, 201.
Fort Scott cement rock, iii, 273, 280.
Fossils, new, from the Kansas Coal Measures, viii, 123.
Four-parameter subgroups of G_6 (Apl) of type V, x, 100, 104.
Freeze-out Hills of Wyoming, Jurassic formation of, ix, 109.
Frenatæ, scales of, iii, 61, 83.
French settlements in Kansas, iii, 161.
French system of registry of criminals, i, 173.
Fusisporium, i, 123, 130.
Future, and future perfect, the past, vii B, 81.

G.

Garnett limestone, named, ii, 100.
Gastrops, vi, 3.
niger, vi, 3.
Geological reconnoissance in southwest Kansas and No Man's Land, ii, 143.
Geological section at Providence, Mo., iv, 161.
Geological section, a, along the Verdigis river, ii, 115.
A. T. & S. F. R. R. from Cherryvale to Lawrence, and from Ottawa to Holliday, ii, 118.
Neosho river, ii, 104.
Geological map of Logan and Gove counties, vii, 19.
Geological map of Kansas, iii, 216.
Geology, report on field-work in, for 1893, ii, 99.
Geometry of one dimension, Hessian, Jacobian and Stinerian in, iii, 103.
German settlements in Kansas, iii, 159, 161.
Glacier, traces of a, at Kansas City, Mo., ii, 149.
Glaciated area of Kansas, a preliminary report on, iv, 153.
Gleed, C. S., i, 187.
Gnamptosilopus, ii, 48.
Gonia, iii, 177.
exul, 180; sequax, iii, 181.
Gove county, geological map of, vii, 19.
Government of American cities, general discussions on bibliography, i, 187.
Graphical construction for the catenary, vii, 211.
Graphic rectification of arcs by means of hyperbolic spiral instrument, vii, 169.
Grapta interrogationis, prothorax of, iii, 138.
Gramineæ, parasites of, i, 131.
Grandgent, C. H., treasurer American Dialect Society, i, 73.
Grass family, number of parasites of, i, 123.
Grasses, notes on some diseases of, i, 123.
Gravels, surface, in eastern Kansas, ii, 136.
Great Spirit spring, i, 85.
Group hG_3 (ABCD), x, 55.
Group eG_3 (ABCD) and its subgroups, x, 45.
Group eeG_3 (ABCD) and its subgroups, x, 46.
Group hG_3 (ABCl) of type II, x, 87.
Group eG_3 (ABCl) of type II, x, 93.

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Group G_4 (ABpl) of type IV, x, 96.
Group G_5 (Apl) of type V, x, 99, 101.
Group G_{77}, x, 31.
G_{24} (1, 2, 3, 4), x, 19, 24.
G_{36} (1, 2, 3), x, 28, 30.
G_{16}, x, 16.
Group of 216 collineations in the plane, x, 13.
Group and subgroups of real collineations leaving a tetrahedron invariant, x, 33.
Gypsum in Kansas, vi, 16.
rocks, chemical composition of some Kansas, vi, 29.

H.

Hadrus lepidotus, parvus, iii, 192.
Harmonic cubics of pencil through nine points, x, 14, 28.
Heating system of Spooner library, University of Kansas, vii, 149.
Hecamede abdominale, vi, 4.
Heliconidæ, iii, 142.
Helophilus bilinearis, iii, 247.
lætus, iii, 243.
latifrons, i, 38; iii, 243.
obscurus, iii, 247.
similis, iii, 243.
sp., iii, 243.
Hemaris thysbe, ii, 52.
clypeus of, ii, 52.
mandibles of, ii, 153.
pilifers of, ii, 55.
Hemaris, prothorax of, iii, 141.
Hepialidæ, scales of, iii, 81, 82.
Hepialus, ii, 52.
clypeus of, ii, 52.
epicranium of, ii, 52.
Hesperornis gracilis, v, 53.
Hessian of the cubic, ii, 88, 89, 91.
Hesperidæ, iii, 142.
Hessian, the, in geometry of one dimension, iii, 103.
Hexachæta, ii, 167.
Himantopus mexicanus, iii, 131.
Holcodus, vi, 183.
Holosaurus, i, 26; iii, 168.
Host Index, Farlow and Seymour's, i, 123, 131.
Hoplopboneus occidentalis, v, 37.
Horsebacks in the Kansas Coal Measures, iv, 145.
Hough, Dr. Gary de N , ix, 203.
House judiciary committee concedes right of senate to originate appropriation bills, ii, 108.
House refuses to recognize right of senate to originate a bill authorizing the issue of treasury notes, ii, 191.
rejects senate amendment to post-office appropriation bill, ii, 198.
resolution denying right of senate to amend revenue bill so as to originate repeal of income tax, ii, 201.
denies right of senate to amend revenue bill so as to alter its purpose, ii, 204.
Hulst, G. D., i, 40.
Hutchinson reformatory, i, 177.
Hygroceleuthus, ii, 1, 23.
afflictus, ii, 23, 24, 25, 26, 155.
ciliatus, ii, 8, 23, 24, 25.
crenatus, ii, 23, 24, 25, 26, 155.
idahoensis, ii, 154.
lamellicornis, ii, 23.
latipes, ii, 23, 24, 155.
table of species, ii, 24.
Hygroceleuthus and Dolichopus, revision of, ii, 1.
additions to revison of, ii, 154.
Hymenoptera, parasitic, vii, 206.
Hyperbolic spiral, constructions for, vii, 156.
graphical operations performed by use of, vii, 160.
Hyposaurus, iii, 3.
Hypothesis for author of Piers Plowman, grounds for new, vii B, 22.
Hystrichodexia rœderi, ii, 77.

I.

Ichthyodectidæ, vii, 21.
Ichthyodectes, vii, 22.
Icterica seriata, ii, 171.
Ilythea flavipes, vi A, 4.
Imperfect and imperfect of repeated action, the descriptive, vii B, 68.
Indians, delicacy of the sense of taste among, ii, 93.
Instrument the, viii, 160.
mathematical properties of, vii, 160.
mechanical properties of, vii, 171.
properties and uses, vii, 155.
Invariant curves and surfaces of hG_1 (ABCD)rs, x, 55.
of hG_1 (ABCl)ar of type II, x, 88.
of G_1 (ABll)an of type III, x, 94.
of G_1 (ABpl)anh of type IV, x, 97.
of G_1 (Apl) of type V, x, 102.
Invariant tetrahedron, x, 33.
Invariants of cubic, ii, 88.
of point and cubic, ii, 85.
of the quartic, ii, 91.
Invertebrate faunas of Jurassic formation in Wyoming, ix, 109.
Invertebrates, Cretaceous, of Kansas, viii, 87.
Injury, mechanical, done by parasite, i, 126.
Inversion, method of, i, 47, 89.
Involutric transformations of the straight line, iv, 111.
Infusoria, relation to oxygen, vii, 111.
Iodine, explosive compound formed by the action of liquid ammonia upon, vi, 71.
Iola limestone, iii, 276, 281.
named, ii, 109.
Irish settlements in Kansas, iii, 161.
Irregular curves, vii, 171.
Irrigation along the Arkansas in western Kansas, iii, 117.
canals along the Arkansas in western Kansas, iii, 123-126.
in western Kansas, problems of, iii, 213.
economic and social influence of, vii B, 27.
Italians in Kansas, iii, 161.
Itomere, formation of, in Scolopendra, x, 68.

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J.

Jacobian of the cubic, ii, 90.
Jacobian, the, in geometry of one dimension, iii, 103.
Joplin lead and zinc district, minerals occurring in, x, 161.
Jugatæ, the scales of, iii, 60, 61, 80.
Jurassic formation in the Freeze-out Hills of Wyoming, ix, 109.

K.

Kafir-corn flour as an adulterant of buckwheat flour, vii, 38.
Kansas Academy of Science, transactions of, i, 85.
Carboniferous, new corals from, vii, 17.
Coal Measures, horsebacks in the, iv, 145.
Cretaceous, fishes of, vii, 21, 115, 177, 191.
list of birds, additions, iii, 129, 130.
Carpodicus mexicanus frontalis, iii, 129, 134.
Dendroica cærulescens, iii, 130, 135.
Hesperocichla nævia, iii, 129, 135.
Piranga ludoviciana, iii, 129, 134.
penology in, i, 155.
present status of the street-paving problem in, ii, 27.
river, notes on the discharge of, iv, 163.
river valley, the sands of, iv, 125.
southeastern, physiography of, vii, 87.
taxation in, viii B, 19.
Kaw river and its tributaries, a chemical examination of, iii, 91.
Kinoplasm and nucleolus, behavior of, in the division of the pollen mother cells of Asclepias cornuti, vii, 77.

L.

Labor problem, experiments in the solution of, iv, 15.
Labyrinthodont, a new, from the Kansas Carboniferous, vi, 209.
Lamm, Oscar F., engineer of Kansas penitentiary, i, 171.
Lamna occidentalis, iii, 2.
Landois, quoted, iii, 50.
Land shales, iii, 277.
Langland, William, his philosophy, ii, 221.
his probable education, ii, 285.
Lasiocampidæ, scales of, iii, 89.
Latin, the sequence of tenses in, viii B, 57.
Lawrence shales, iii, 277, 282, 284, 295.
coal in, iii, 303, 305.
named, ii, 122.
Lecaniodiaspis celtidis, sub. sp. pruinosus, sub. sp. n., viii, 77.
Lecanium armeniacum, viii, 71.
canadense, viii, 68.
cockerelli, n. sp., viii, 70.
coffeæ, viii, 75.
hesperidium, viii, 75.
kansasense, n. sp., viii, 69.
macluræ, n. sp., viii, 67.
oleæ, viii, 75.
Lecaniodiaspis? parrotti, n. sp., viii, 76.
Lecompton limestone, iii, 278.
Legal status of American cities, bibliography, i, 184.
Lepidoptera, the prothorax of, dorsal aspect, iii, 137.
form, variation, iii, 138.
lobes of, iii, 137, 138.
membrane, movements of, iii, 137.
taxonomic value of the scales of, iii, 45.
width of, iii, 138.
Leptecodon rectus, n. sp., viii, 113.
Leptorhethum, ii, 50.
angustatum, ii, 50.
Le Roy shales, named, ii, 110.
Lesticodus, vi, 182.
Lestosaurus, vi, 184.
Limacon, article on the, i, 89.
as a nodal bicuspidal quartic, i, 62.
Pascal's, i, 60, 89.
angle trisected by use of, ii, 39.
Limestone, Burlington or Garnett, iii, 277, 281.
Carlyle, iii, 277.
characteristics of Coal Measures, iii, 280.
Cottonwood Falls, iii, 279, 283, 280.
Erie or triple, iii, 275, 280.
Iola, iii, 276, 281.
Lecompton, iii, 278.
Oread, iii, 278, 281.
Oswego, iii, 273, 280.
Pawnee, iii, 274, 280.
Tecumseh, iii, 278.
Topeka, iii, 278.
Limestone, sandstone, and shales, relative value for stratigraphic work, ii, 102.
Limnobia concinna, ii, 60.
conctipes, ii, 61.
Linear geometry of the cubic and quartic, ii, 85.
Lintel, maximum load on a, ii, 31.
Liodon, iii, 166.
Lipochæta, vi, 7.
Literature and the writer's responsibility, the tone of, vii B, 39.
Livingston, Edward, quotation from, i, 161.
Local government, bibliography, i, 180.
Logan county, geological map of, vii, 19.
Logarithmic curve, construction for, vii, 220.
use of, in plotting the catenary, vii, 218.
London, government of, bibliography, i, 181.
Lordotus pulcherrimus, puella, ii, 64.
Lords and commons, contest between, over control of the purse, ii, 213.
Louisville mineral water, the composition of, vi A, 117.
Loup Fork tortoises, skull of, vii, 143.
Loxia curvirostratra minor, iii, 134.
stricklandi, iii, 134.
Lycænidæ, iii, 140, 141.

M.

Machærodus, iii, 170.
Macrosaurus, vi, 182.
crassidens, iii, 175.

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Magnetism, effect upon the spectral lines of sodium, vi, 77.
Mallota albipilis, iii, 244.
Map, preliminary, of foreign settlements in Kansas, i, (facing) 84.
Marginal areas, extent of, iii, 283.
Mastodonsaurus, vi, 209.
Maximum load on a lintel, ii, 31.
McCann sandstone, stratigraphy of the, ix, 175.
Mechanical properties of hyperbolic spiral instrument, vii, 171.
Mecoptera, scales of, iii, 59.
Megalopteris, systematic description of, x, 7.
Megalopygidæ, scales of, iii, 84.
Melanerpes torquatus, iii, 133.
Melanoplus differentialis, vii, 205, 206, 207.
parasitic influences on, vii, 205.
Melanostoma concinnum, iii, 229.
kelloggi, iii, 230.
mellinum, i, 35; iii, 230.
stegnum, i, 35.
Melitera dentata Grote, notes on, i, 39.
prodenialis Walker, i, 39, 40.
Mesogramma marginatum, i, 37; iii, 239.
politum, iii, 239.
Metapelastoneurus, ii, 152.
kansensis, ii, 153.
Microdon megalogaster, i, 34.
Micropterygidæ, scales of, iii, 82, 83.
globosus, iii, 225.
Microscopic comparison of samples of white arsenic, ix, 255.
Minerals in the Joplin district, ix, 161.
Mineral water, composition of Louisville, vi, 117.
Miocene, the White River, of Wyoming, a new species of Dinictis from, iv, 237.
Mixogaster mexicana Macq., notes on, vi, 140.
breviventris, n. sp., vi, 137.
conopsoides Macq., notes on, vi, 140.
previously described species of, vi, 140.
Modern higher algebra, i, 133.
Modiola, sp. ?, viii, 91.
Moments, maximum bending, for moving loads, etc., i, 143.
Money bills, origination of, confined to lower house, ii, 176.
provisions in state constitutions, ii, 177.
Mongolians, temperature sense in, iii, 208.
Monocular perception of space, v, 112, 117.
Monopteria gibbosa Meek and Worthen, new variety of, vii, 187.
Monopteria ? subalata, n. sp., viii, 133.
Monroe doctrine, history of, v, 56.
Morosaurus grandis, vii, 173.
sacrum of, vii, 173.
species of, vii, 173.
Mosasauridæ, iii, 169.
Mosasaurus maximiliani, iii, 166.
horridus, iii, 166; vi, 95.
Mosasaurinæ, vi, 181.
Mosses, method of demonstrating distribution of spores, vii, 113.
Mosasaurs, a new genus of, vi, 95.
habits of, vi, 110.
Kansas, part I, i, 15.
Kansas, part II, ii, 83.
new characters of, vii, 235.
range and distribution of, vi, 177.
restoration of, vi, 107.
some additional characters of, viii, 39.
Mounting media, refractive index and alcohol-solvent power of, vii, 197.
Multisection of angles by use of hyperbolic spiral instrument, vii, 162.
Municipal government in the United States, a brief bibliography of, i, 179.
Municipal industries of American cities, bibliography, i, 191.
Muscidæ, South American, ix, 203.
Myalina ? exasperata, n. sp., viii, 128.
Mycelium, methods of entering host, i, 127.
Mydaidæ, mouth-parts of, i, 113.
Mylodon harlani, iii, 175.
Myology of the hind limb of the raccoon, vi, 121.
Myriapods, spermatogenesis of, x, 61-76.
Mytilaspis pomorum, viii, 14.
Myxomycetes, material for the study of, vii, 111, 112.

N.

Natural gas and coal-oil in Kansas, iv, 1.
distribution and use of, iv, 10.
method of collecting and analyzing, iv, 9.
Nausigaster punctulata, iii, 247.
Navicula, i, 87.
Nebraska City section, correlation of, vii, 231.
Nectoportheus, vi A, 182.
Nemistriuidæ, mouth-parts of, i, 114.
Neoglaphyroptera striata, ii, 60.
Neoitamus affinis, distinctus, ii, 73.
Neuropteris, systematic description of, x, 7.
New forms of Pseudomonotis from the Upper Coal Measures of Kansas, viii, 79.
New labyrinthodont from the Kansas Carboniferous, vi, 209.
New Plesiosaur from the Kansas Comanche Cretaceous, vi, 57.
New York system of classifying prisoners, i, 160.
municipal government of, bibliography, i, 194.
Niobrara Cretaceous, iii, 21.
Nitzschia, i, 87.
No Man's Land, geological reconnoissance in, ii, 143.
Normal forms of projective transformations, vii, 125.
Note on the Permian flora of Kansas, ix, 63.
Notes on the osteology of Bison antiquus, vi, 127.
Notice of some vertebrate remains from the Kansas Permian, vi, 53.
Notiphila bellula, vi, 5.
pulchrifrons, vi, 5.
striata, vi, 5.
Nucleus, budding of, in Scolopendra, x, 73.

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Nucula pulchella, n. sp., viii, 132.
Nusa abdominalis, vi, 103.
  similis, vi, 103.
Nyctodactylus, i, 5.
  species of, i, 2.
Nymphalidæ, iii, 142.

O.

Oats, number of parasites of, i, 123.
Ochthera, humilis, vi, 6.
  regalis, vi, 6.
Occurrence of the bryozoan genus Rhabdomeson in America, ix, 173.
Oedaspis, ii, 165.
  atra, ii, 164.
  minuta, ii, 164.
  montana, ii, 163.
Oedicarena, ii, 162.
  diffusa, ii, 161, 162.
Oklahoma, a geological reconnoisance in Grant, Garfield and Woods counties, vii, 121.
Oligoporus? minutus, n. sp., viii, 126.
Omegasyrphus baliopterus, iii, 226.
  coarctatus, iii, 226.
  sp., iii, 226.
One-parameter subgroups of $hG_3(ABCD)$, x, 33.
  of $hG_3(ABCl)$ of type II, x, 87.
  of $eG_3(ABCl)$ of type II, x, 92.
  of $G_3(ABl')$ of type III, x, 93.
  of $G_4(ABpl)$ of type IV, x, 96.
  of $G_6(Apl)$ of type VI, x, 100, 102.
On the construction of collineations, ix, 65.
Onychogonia, iii, 180.
Oospores, obliteration of parenchyma by, i, 129.
Opercular and other cranial bones of Xiphactinus Leidy, a preliminary description of, viii, 19.
Opetia, iii, 143.
Opuntia missouriensis, i, 39, 40.
Oread limestone, iii, 278, 281.
  named, ii, 123.
Organic matter in the Western streams, iii, 101.
Origination of money bills, debates on, in constitutional convention, ii, 176.
Ornithocheiroidea, vi, 36.
Ornithocheirus, vi, 35.
Ornithostoma, ii, 79; vi, 35.
  ingens, vi, 36.
  notes on the mandible of, iv, 61.
    on the skull of, iv, 195.
Orthoneuromyia, ii, 67.
  modesta, ii, 68.
Osage City shales, iii, 278-305.
  coal in, iii, 278, 304, 305.
Oscillaria, i, 87.
Osteology of Anogmius polymicrodus Stewart, viii, 117.
Ostreidæ, viii, 95.
Oswego limestone, iii, 273, 280.
Ottawa limestone, named, ii, 121.
Ostrea attenuata, n. sp., viii, 99.
  canonensis, n. sp., viii, 90.
  congesta, viii, 90.
  crenula, n. sp., viii, 93.
  ellsworthensis, n. sp., viii, 88.
  exogyroidea, n. sp., viii, 91.
  incurva, n. sp., viii, 92.
  jewellensis, n. sp., viii, 95.
  kansasensis, n. sp., viii, 88.
  lata, n. sp., viii, 94.
  leeli, n. sp., viii, 94.
  wellerii, n. sp., viii, 89.
  willistonii, n. sp., viii, 89.
Oxygen, evolution of, by Algæ, vii, 111.

P.

Pachyrhina erythrophys, ii, 63.
Pachyrhizodus leptognathus, vii, 193.
  minimus, a new species of fish from the Cretaceous of Kansas, viii, 87.
  sp., vii, 195.
  velox, vii, 193.
Packing-house, condition of employees in, iv, 41.
Pamphila conardus, genæ of, ii, 52.
  epicranium of, ii, 53.
Pangonia arcuata, iii, 190.
  bullata, iii, 191.
  diaphana, iii, 190.
  filipalpis, iii, 190.
  fulvithorax, iii, 189.
  margaritifera, iii, 191.
  pyrausta, iii, 189.
  unicolor, iii, 189.
  venosa, iii, 189.
Panicum sanguinale, i, 129.
  variegatum, i, 125.
Papilis eurymedon, prothorax of, iii, 140.
Papilionidæ, iii, 142.
Paragus bicolor, i, 35; iii, 227.
  tibialis, iii, 227.
Paralimna multipunctata, vi A, 111.
  obscura, vi A, 5.
Paramyia, vi A, 1.
Parasidæ, scales of, iii, 87.
Parasites, effects of, on hosts, i, 130.
Paris, government of, bibliography, i, 182.
Partition of Africa, the, viii B, 1.
Parydra humilis, vi, 7.
Pascal's Limacon, i, 60, 89.
Patrick, G. E., i, 89.
Pawnee limestone, iii, 274, 280.
Pedal of a circle, i, 89.
Pelastoneurus, ii, 152.
  vagans, ii, 152, 153.
Pelecocera, iii, 187.
  pergandei, iii, 187.
  scæ oides, iii, 187.
  willistoni, iii, 187, 239.
Pelecorhynchus ornatus, iii, 192.
Pelecypods, new and little known, from the Coal Measures, viii, 131.
Pencil of cubics through nine points, x, 13.
Penitentiary, Kansas state, i, 155.

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Pennsylvania system of classifying prisoners, i, 160.
Penology in Kansas, i, 155.
Perception, visual, of distance, v, 119.
Percolation through soils, iii, 221.
Permian, the, in southern Kansas, vi, 149.
Permian plants—Tæniopteris of the Permian of Kansas, x, 1.
Permian flora of Kansas, note on, ix, 63.
Permian of Kansas, a new genus of ferns from the, ix, 179.
Peronospora graminicola, i, 129.
Petroleum, composition of Kansas, iv, 11.
Philadelphia, municipal government of, bibliography, i, 196.
Phorocera, iii, 185.
Physiography of southeastern Kansas, vii, 87.
Physogenua ferruginea, vi, 8.
  nigra, vi, 8.
  vittata, vi, 8.
Pica pica hudsonica, iii, 133.
Picicorvus columbianus, iii, 133.
Pieris rapæ, prothorax of, iii, 137, 140.
Piers the Plowman:
  content of the poem, ii, 239.
  form of the poem, ii, 276.
  interpretation of the character, ii, 251.
  political and social theories in, ii, 243.
  relation of, to the life of the author, ii, 235.
  scientific information in, ii, 239.
  spirit of the poem, ii, 279.
  theology and religion in, ii, 248.
  value of the poem, ii, 288.
Piers Plowman, the vision of, ii, 233.
  list of works referring to, vii B, 1.
  notes on, vii B, 1.
  possible name of author, vii B, 25.
  scene of the poem, ii, 234.
Pipiza pistica, iii, 227.
Piricularia grisea, i, 129.
  effect of, i, 130.
  hosts of, i, 131.
Plagiotoma obliqua, ii, 162.
Plants, Permian—Tæniopteris of the Permian of Kansas, x, 1.
Plasmodia of Myxomycetes, material for the study of, vii, 111, 112.
Platecarpinæ, vi, 181.
Platecarpus, vi, 101-108, 183; vii, 203.
  note on, vii, 235.
  tympaniticus, vi, 185.
Platinum, solubility of, in hydrochloric acid, iii, 199.
Platychirus chætopodus, iii, 231.
  ciliatus, iii, 247.
  hyperboreus, iii, 231.
  palmulosus, iii, 231.
  peltatus, iii, 231.
Platycnema, iii, 143.
Platygonus alemanni, iii, 24.
  bicalcaratus, iii, 24.
  compressus, iii, 24.
  condoni, iii, 24.
  restoration of, iii, 23.
Platygonus striatus, iii, 24.
  vetus, iii, 24.
  zeigleri, iii, 24.
Platypeza abscondita, iii, 205.
  anthrax, iii, 145, 205.
  barbata, iii, 207.
  boletina, iii, 149.
  calceata, iii, 144.
  cinerea, iii, 146, 150.
  egregia, iii, 146, 150.
  flavicornis, iii, 145.
  obscura, iii, 145.
  ornatipes, iii, 143, 207.
  pallipes, iii, 145.
  pulchra, iii, 144.
  pulla, iii, 205.
  rectinervis, iii, 207.
  superba, iii, 207.
  tæniata, iii, 145, 149.
  unicolor, iii, 205.
  umbrosa, iii, 145, 148.
  velutina, iii, 143, 205.
Platypezidæ, iii, 143, 205.
Platystoma lunulata, ii, 165.
Platyura pulchra, ii, 59.
  gracilis, ii, 60.
  notabilis, ii, 59.
Pleasanton shales, iii, 274, 275, 286, 293, 295, 302, 305.
  coal in, iii, 302, 305.
Plesiosaurs, Cretaceous, iii, 2.
Plesiosaurus gouldii, vi, 57.
Plioplatecarpus, i, 28.
Pluperfect, the aoristic, vii B, 79.
  the descriptive, vii B, 75.
Pogonodon, sp., iii, 173.
Pollen mother cells of Asclepias cornuti, behavior of kinoplasm and nucleolus in division of, vii, 77.
Pollicipes haworthii, vi, 188.
Polymorphomyia, ii, 165.
Polygons, construction of, with the hyperbolic spiral instrument, vii, 168.
Pomacera, 1, 102.
Portheus, vii, 22, 115.
  lowii, vii, 24.
Porzana jamaicensis, iii, 131.
Posidonomya? pertenuis, n. sp., viii, 127.
  recurva, n. sp., viii, 126.
Pottawatomie and Douglas formations along the Kansas river, the, ix, 234.
Power of a twelve-foot windmill, vi, 191.
Preliminary notice of the Meek and Marcou section at Nebraska City, Neb., with the Kansas Coal Measures, vii, 231.
Preliminary description of seven new species of fish from the Cretaceous of Kansas, vii, 191.
Prentis, Noble, i, 71.
Presents, perfects, and futures, vii B, 89.
Preservatives, action of salicylic acid and calcium sulfite in the preservation of cider, vi A, 111.
Providence, municipal government of, i, 196.

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Progress and activity of society dependent upon abundance of food supply, vii B, 28.
Projective groups of perspective collineations in the plane, v, 1.
Projective transformations, canonical forms of, vii, 132, 140.
continuous groups of, treated synthetically, iv, 71, 243.
continuous groups of, v, 81.
essential parameters of, vii, 125, 126.
normal forms of, vii, 125.
of the plane, five types of, viii, 43-59.
types of (plate), vii, 127.
types of, vi, 63.
Protosophyræna bentonia, vii, 27.
Cretaceous species of, vii, 29.
gigas, n. sp., viii, 110.
recurvirostris, vii, 191.
sp. nov., vii, 28.
Protoparce carolina, ii, 52.
clypeus, ii, 52.
genæ of, ii, 52.
mandibles of, ii, 53.
occiput of, ii, 53.
pilifers of, ii, 55.
post genæ of, ii, 54.
Prothorax of butterflies, a study of the, iii, 137
Protochœrus prismaticus, iii, 24.
Protostega, iii, 10.
Pseudogonia, iii, 179.
Pseudo-germinal vesicle stage in Scolopendra, x, 64.
Pseudomonotis from the Upper Coal Measures of Kansas, viii, 79.
hawni, viii, 83.
hawni equistriata, n. var., viii, 82.
? robusta, n. sp., viii, 82.
(?) tenuistriata, n. sp., viii, 81.
Pseudo-perna, n. gen., viii, 95.
attenuata, n. sp., viii, 97.
orbicularis, n. sp., viii, 97.
rugosa, n. sp., viii, 96.
torta, n. sp., viii, 96.
Psilopa aciculata, vi 4.
metallica, vi, 4.
nigrimana, vi, 4.
Psilopus, ii, 50.
character of, ii, 47.
name preoccupied, ii, 48.
bicolor, ii, 48.
filipes, ii, 48.
scintillans, ii, 48.
tener, ii, 48.
Psilopinæ, new genera and species of, ii, 47.
table of genera, ii, 48.
Psychidæ, scales of, iii, 85, 86.
Pteranodon, ii, 79; vi, 35.
pubis of, i, 4.
species of, i, 1.
skull of, i, 3.
umbrosus, vi A, 36.
Pteranodontinæ, i, 12.
Pterodactyls, Kansas, i, 1.
Kansas, part II, ii, 79.
Pterodactylus, i, 8, 11.
Pterosauria, vi, 36.
classification of, i, 12.
Pterycollasaurus, iii, 166.
Puccinia coronata, i, 126.
graminis, hosts of, i, 132.
number of species on grasses, i, 124.
phragmitis, i, 125.
rubigo-vera, hosts of, i, 132.
Puccinias, effects of, i, 130.
Pumping power of windmills, theoretical and measured, iv, 93.
Pyromorphidæ, scales of, iii, 88, 89.

Q.

Quartics, basal points of a system of, i, 66, 69.
critic centers of a system of, i, 66, 68.
nodal bicuspidal, i, 59, 62.
tricuspidal, i, 62, 65.
trinodal, i, 56, 59.
with a triple point, i, 65, 66.

R.

Rainfall in Kansas, iii, 117, 218.
"Raise" debates on the meaning of, in the constitution, ii, 188, 193, 207, 210.
Range and distribution of the Mosasaurs, with remarks on synonymy, vi, 177.
Ratio of limestone to shales and sandstones, iii, 279.
Reaumuria, iii, 177.
Rectification of arcs with hyperbolic spiral instruments, vii, 169.
Reformatory at Elmira, N. Y., i, 160.
Reformatory at Hutchinson, i, 160.
Reformatory inmates, biographical statistics of, i, 166.
Reform school at Topeka, i, 160.
Refractive index of clearing and mounting media, vii, 197.
Registry of criminals, system of, i, 173.
Regular polygons, construction of, by means of hyperbolic spiral instruments, vii, 168.
Relative sentences and clauses, coordinate (in Cæsar's Commentaries), vii B, 101.
Relative value of limestone, sandstone and shale for stratigraphic work in Kansas, ii, 102.
Responsibility for financial legislation, effect of business methods of Congress on, ii, 221.
rendered ineffectual by present methods, ii, 223.
reforms suggested to secure, ii, 226.
Responsibility, the tone of literature and the writer's, vii B, 39.
Restoration of Kansas Mosasaurs, vi, 107.
Restoration of Oreodon culbertsonii Leidy, vi, 13.
Restoration of Ornithostoma, vi, 35.
Results of an examination of Tacitus and Sallust on sequence of tenses, vii B, 108.
Rhabdomeson in America, occurrence of the bryozoan genus, ix, 173.

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Rhabdopselaphus, iii, 42.
Rhadiurgus leucopogon, ii, 75.
Rhagoletis pomonella, ii, 164, 165.
zephyria, ii, 164.
Rhaphidolabis debilis, ii, 62.
Rhaphiomidas, mouth-parts of, i, 111.
acton, i, 111, 112.
Rhedia, iii, 177.
Rhingia nasica, i, 37; iii, 240.
Rhinochelys, iii, 8.
Rhynchogonia, iii, 189.
Riley, C. V., i, 39.
River waters, comparison of, iii, 99.
comparison of mineral constituents in water of Kaw valley, iii, 98.
Robert Langley, name, vii B, 25.
Robinett flags, named, ii, 108.
Roulette, instantaneous center of, i, 90.
limacon as a, i, 89.
Ruins in Scott county, Kansas, some prehistoric, vii B, 109.
Russians in Kansas, iii, 159, 161.

S.

Sacrum of Morosaurus, vii, 173.
Sagenodus, a new species of, from the Kansas Coal Measures, viii, 175.
copeanus, n. sp., viii, 178.
Salicylic acid and calcium sulfite as preservatives of cider, vi A, 211.
Salmon, reference to higher plane curve of, i, 48, 58, 60, 70, 89.
reference to conic sections of, i, 50.
Sands of the Kansas river valley, iv, 125.
Saprolegnieæ, material for the study of, vii, 112.
Sapromyza bipunctata, vi, A, 11.
contigua, vi, 9.
exul, vi, 11.
geminata, vi, 9.
lupulinoides, vi, 11.
macula, vi, 9.
picrula, vi, 10.
rubescens, vi, 9.
xanthiceps, vi, 9.
Sarcophagæ, vii, 208, 209.
Sarcophaga cimbicis Town, vii, 206.
hunteri, n. sp. Hough, vii, 207, 209, 210.
Sarcophagidæ, vii, 206.
Saurocephalidæ, vii, 21.
Saurocephalus, vii, 22, 177.
dentatus, vii, 25.
species of, vii, 186.
Saurodon, vii, 22.
ferox, vii, 183.
leanus, vii, 177.
notes on the genus and allied species, vii, 177.
species of, vii, 186.
xiphirostris, vii, 178.
Saurodontidæ, vii, 21.
Saurodontidæ Cope, remarks on, viii, 107.
Scandinavian settlements in Kansas, iii, 159, 161.
Scales, absence of, in Coleoptera, iii, 74.
in Heliconidæ, iii, 75.
in Hemaristhysbe, iii, 74.
in Luna, Promethea, iii, 74.
in Sesiidæ, Zygænidæ, iii, 73.
arrangement of, in Callidryas eubule, Grapta interrogationis, Lycænidæ, Morpho, Papilio, iii, 48.
coloration in Arachnis picta, iii, 71, 72.
Epicallia, Euprepia, Halesidota ardentata, iii, 72.
Lycæna, Micropteryx, Morpho, iii, 70.
cups of insertion of, in Casina, Erebus strix, Eudamus tityrus, Micropteryx unimaculella, Morpho, Pieris protodice, iii, 49.
of body of, Chærompa, Megalopyge, Phylampelus, Sphingidæ, iii, 75.
of Lepidoptera, absence of, iii, 73.
arrangement of, iii, 47, 48.
body scales, iii, 75.
coloration by, iii, 69.
comparison of, in Coleoptera, iii, 74.
development of, iii, 63, 64.
functions of, iii, 54, 57, 76.
histology of, iii, 51.
ornamental, iii, 68.
pedicels of, iii, 50.
shape of, iii, 47.
significance of development of, iii, 67.
specialization of, iii, 64, 65.
striæ of, iii, 51, 52.
structure, iii, 52, 53.
taxonomic value of, iii, 45, 79.
variation of, iii, 53, 54.
shape and size of, in Lepidoptera, iii, 46.
in Callidryas eubule, iii, 47, 48.
Castnia, Micropteryx, Morpho, iii, 47.
specialization in Actias luna, iii, 68.
in Citheronia regalis, iii, 69.
in Gloveria, iii, 65.
in Heliconia, iii, 67.
in Prionoxystus robiniæ, iii, 64.
in Saturnia carpini, iii, 63.
in Tolype, iii, 66.
striæ of Callidryas eubule, iii, 52.
Castnia, iii, 53.
Danais archippus, iii, 51.
Hepialus, iii, 52.
Lycomorpha constans, iii, 52.
Micropteryx, iii, 70.
Morpho, iii, 51.
Nomophila, iii, 52.
variation in Actias luna, Danais archippus, Megalopyge crispata, Micropteryx, Tolype velleda, iii, 53.
Scatella obscura, vi, 5.
stagnalis, vi, 5.
Scholar in politics, the duty of, v, 55.
Schools in a foreign tongue in Kansas, iii, 162.
Scientific publications by members of the University of Kansas, bibliography of, viii, 138; x, —.
Scotch settlements in Kansas, iii, 162.

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Scolopendra, notes on spermatocytes and spermatids of, x, 61, 76.
accessory chromosome in, x, 71.
apical point in spermatocytes of, x, 66, 67,
budding of nucleus in, x, 68.
formation of itomere in, x, 68.
origin of axial filament in, x, 70-74.
pseudo-germinal vesicle stage in, x, 64.
structure of testes of, x, 62.
Scott county, Kansas, some prehistoric ruins, vii B, 109.
Secretary of the treasury forced to make regular reports, ii, 185.
Selasoma tibialis, iii, 192.
Semi-arid Kansas, iii, 209.
Semper, Carl, quoted, iii, 62.
Senate declines to originate a tariff bill, ii, 192.
attempts to originate general appropriation bill, but fails, iii, 194.
Sense of taste, comparison of the results in the case of tests on Indians and on whites, iii, 97.
Sequence, exceptions to, vii B, 96.
Sequence feeling, the proof of a, vii B, 103.
Sequence of tenses in Latin, the, vii B, 57.
Sericomyia militaris, i, 37; iii, 242.
Servant-girl problem, iv, 31.
Setaria glauca, i, 123.
viridis, i, 129.
Settlements, foreign, in Kansas, i, 71.
Sexes, delicacy of the sense of taste in the different, compared, ii, 97.
Shales, origin of, iii, 285, 286.
Cherokee, iii, 272-309.
Lane, iii, 277.
Lawrence, iii, 277-295.
Osage City, iii, 278-305.
Pleasanton, iii, 274-305.
Thayer, iii, 275-305.
Sheldon, E. S., i, 137.
Sialia arctica, iii, 135.
Sironectes, iii, 168.
Skeat, W. W., vii B, 1, 8, 11, 12, 20.
Skin of Tylosaurus, vi A, 97.
Slosson, E. E., i, 137.
Smith, J. B., i, 39, 40.
Smut on corn, i, 126.
Snow, F. H., i, 39.
Snowia, i, 119; vi, 12.
rufescens, i, 120.
Soderstrom, E. E., i, 137.
Sodium, effect of magnetism upon the spectral lines of, vi, 77.
Solanum carolinense, ii, 161.
Solenomya parallela, n. sp., viii, 131.
trapezoides, viii, 132.
Somphospongia, n. gen., viii, 128.
multiformis, n. sp., viii, 128.
Some new cirriped crustaceans from the Niobrara Cretaceous of Kansas, vi 187.
Sound, experiments in judging the direction of, vii, 9.
Spallanzania, iii, 177.
Sound, experiments in judging the distance of, vii, 1.
South American Muscidæ in the collection of S. W. Williston, ix, 203.
Spartina cynosuroides, i, 125.
stricta, i, 125.
Spathichira, ii, 23.
funditor, ii, 23.
pulchrimana, ii, 23.
Special senses, delicacy of, ii, 85.
Spectral lines of sodium, effect of magnetism upon, vi A, 77.
Spermatids of Scolopendra, x, 68-71.
Spermatocytes of Scolopendra, x, 63-68.
Spermatogonial divisions in Brachystola magna, ix, 135.
Sphærophoria cylindrica, i, 37; iii, 239.
Sphecomyia vittata, iii, 247.
Sphingidæ, iii, 141.
Sphinx ligustri, mouth-parts of, ii, 55.
Sphiximorpha Rond, vi, 146.
Spilomyia kahli, iii, 245.
liturata, iii, 245.
quadrifasciata, i, 38.
Spilographa, ii, 162.
electa, ii, 161, 162.
Spirifer cameratus Morton, variations of external appearance and internal characters, vii, 103.
Spooner library, heating plant of, vii, 149.
Spogostylum, iii, 43.
Squama, vi, 187.
lata, vi, 188.
spissa, vi, 187.
Statistics of American cities, bibliography, i, 185.
biographical, of reformatory inmates, i, 166.
Stegana, vi, 12.
Stein, Paul, vii, 209.
Steinerian, the, in geometry of one dimension, iii, 103.
Stibasoma theotænia, iii, 194.
Steiner, a theorem due to, i, 70.
Stenoprosopus arizonensis, ii, 76.
Stictocephala, ii, 170.
Straight line, involutoric transformations of, iv, 111.
Stramentum, vi, 188.
haworthi, vi, 188.
tabulatum, vi, 189.
Stratigraphy of eastern Kansas, resume of, ii, 126.
of the McCann sandstone, ix, 175.
of the Freeze-out Hills of Wyoming, ix, 109.
of Cherokee shales, iii, 272.
of Coal Measures, iii, 271.
resume of coal beds of, iii, 305.
Stratigraphic work, relative value of limestone, sandstone and shales for, ii, 102.
Straussia longipennis, ii, 159.
varieties of, ii, 159-161.
Strawn limestone, named, ii, 110.

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Street-paving problem in Kansas, present status of the, ii, 27.
Stygeropis bergrothi, ii, 64.
Stylogaster, the American species of, i, 120.
Strychnine, action of sulfuric acid on the separation of this alkaloid from organic matter, vi A, 205.
Subgroups of hG_3 (ABCD) with invariant family of cones, x, 37.
with invariant family of ruled surfaces, x, 38.
with invariant family of quadric surfaces, x, 42.
with invariant family of quadric cones, x, 42.
whose path-curves are conics, x, 43.
whose path-curves are twisted cubics, x, 44.
Subgroups of types VIII, IX, XI, in hG_3(ABCl) of type II, x, 90.
VI, VII, X, in hG_3 (ABCl) of type II, x, 91.
VIII, IX, VII, X, in eG_3 (ABCl) of type II, x, 92.
VII, X, in G_3 (ABll′) of type III, x, 96.
IX, XI, in G_3 (ABll′) of type III, x, 95.
XIII, XII, VII, in G_4 (ABpl) of type IV, x, 98.
XIII, XII, VII, in G_6 (Apl) of type V, x, 100, 105.
Subgroups of G_3 (ABll′) with transcendental invariant surfaces, x, 94.
of G_3 (ABll′) with invariant quadric surfaces, x, 95.
of G_6 (Apl) of type V, x, 100.
Subjunctive constructions, some developed, v B, 86.
Summary of results on sequence of tenses, vii B, 95.
Summary of results upon spermatocytes and spermatids of Scolopendra, x, 74–76.
Supplementary list of N. A. Syrphidæ, iii, 249.
Sympycnus, table of species, ii, 153.
frontalis, ii, 153.
lineatus, ii, 153.
nodatus, ii, 153.
occidentalis, ii, 153.
tertianus, ii, 153.
Syritta pipiens, i, 38; iii, 245.
Syrphus amalopsis, iii, 247.
americanus, i, 37; iii, 236.
arcuatus, i, 36; iii, 232.
creper, iii, 234.
digregus, iii, 233.
disjectus, i, 36; iii, 234.
intrudens, iii, 232.
montivagus, opinator, iii, 236.
notes and description of, i, 33.
pauxillus, i, 37; iii, 247.
pullulus, iii, 237.
ribesii, i, 37; iii, 235.
ruficauda, i, 36; iii, 234.
sodalis, iii, 247.
umbellatarum, i, 37; iii, 237.
Systropus, iii, 42.
Syrphidæ, new species of, vi, 137.
list of N. A., iii, 249.
of Colorado and New Mexico, iii, 215.

T.

Tabanus festivus, iii, 195.
importunus, iii, 195.
leucaspis, iii, 195.
modestus, iii, 195.
quadripunctatus, iii, 195.
nigrum, iii, 195.
unicolor, iii, 195.
Tabanidæ, exotic, iii, 189.
Tachinidæ, vii, 206.
fissicorn, iv, 171.
Tæniopteris coriaceæ, x, 2.
coriaceæ, var. linearis, n. var., x, 3.
newberriana, x, 4.
sp., x, 5.
interneural bodies on fronds of, x, 5.
other species of, x, 7.
scars on or near the rachis of, x, 9.
Talarocera nigripennis Wied., iv, 171.
Tapinocera, i, 102.
Taste, delicacy of, among Indians, ii, 95.
method of testing the delicacy of, 11, 95.
Taxation in Kansas, viii B, 19.
Taxonomic value of the scales of Lepidoptera, iii, 45.
Tecumseh limestone, iii, 278.
Teeth from the Kansas Cretaceous, some fish, ix, 27.
Temnostoma æquale, iii, 247.
Temperature sense, the, iii, 201.
Tenses in sequence, the remaining, vii B, 91.
Tenses of repeated action depending on similar tenses, vii B, 87.
Tephritis affinis, ii, 172.
albiceps, ii, 173.
finalis, ii, 172.
obscuripennis, ii, 174.
picturata, ii, 173.
Tephromyia, vii, 207, 209.
affinis Fall., vii, 209, 210.
grisea Meig., vii, 209.
lineata Fall., vii, 209, 210.
obsoleta Fall., vii, 209, 210.
Terminology of spermatogenesis of myriapods, x, 61.
Tertiary, Loup Fork, ii, 289.
Pliocene, ii, 289.
of Kansas, iii, 216.
Testes of Scolopendra, structure of, x, 62.
Tests of windmills, vi, 89.
Tetracaulodon (Tetrabelodon) shepardii Cope, viii, 99.
Tetrad formation in spermatocytes of Scolopendra, x, 73.
Thayer shales, iii, 276, 295, 302, 305.
Theory of compound curves in railroad engineering, v, 99.
The spermatocyte divisions of the Acrididæ, ix, 73.
Therevidæ, mouth-parts of, i, 14.

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Three-parameter subgroups of G_4 (ABpl) of type IV, x, 97.
of G_6 (Apl) of type V, x, 100, 104.
Thucydides, composition of verbs with prepositions in, v, 119.
Tin, the detection of arsenic, antimony, and, ix, 259.
Tolmerus callidus, ii, 75.
notatus, ii, 74.
Topeka limestone, iii, 278.
Topography of eastern Kansas, ii, 120.
Toxochelys latiremis, vii, 201.
Toxotrypana curvicauda Gerst., iv, 117.
Townsendia minuta, n. sp., iv, 108.
gen. nov. (Asilidæ), iv, 107.
Townsend, reference to modern geometry of, i, 47.
Transactions American Entomological Society, i, 40.
Kansas Academy of Science, i, 85.
Triassic of Kansas, iii, 216.
Trichoptera, scales of, iii, 58, 59, 61.
Triclonineæ, i, 105.
Triclonus, i, 104, 106.
bispinifer, mouth-parts of, i, 113.
Triodonta curvipes, iii, 247.
Triplasius, iii, 42.
Tripsacum dactyloides, i, 123.
Triptotricha, iii, 263.
Triptogon modesta, genæ of, ii, 52.
clypeus of, xii, 52.
gula of, ii, 54.
labium of, ii, 57.
maxillæ of, ii, 57.
Trisection of an angle, ii, 35.
Tropidia incana, iii, 244.
Trypeta, sp., ii, 163.
æqualis, ii, 171.
florescentiæ, ii, 163.
occidentalis, ii, 163.
palposa, ii, 159, 162, 163.
Trypetidæ, North American, descriptions of, with notes, ii, 159.
Turtle, Cretaceous, iii, 2.
a new, from the Benton Cretaceous, iii, 5.
remains from the Fort Pierre, vii, 201.
Tylosauridæ, iii, 169.
Two new species of Asilids from New Mexico, vi, 103.
Two new crinoids from the Kansas Carboniferous, ix, 21.
Two-parameter subgroups of hG_3 (ABCD) x, 37.
of G_3 (ABCl) of type II, x, 92.
of G_3 (ABll′) of type III, x, 94.
of G_4 (ABpl) of type IV, x, 97.
of G_6 (Apl) of type V, x, 100, 105.
Tylosaurinæ, vi, 180.
Tylosaurus, vi, 109, 182.
extremities of, vi, 97.
proriger, vi, 102.
Types of projective transformations in the plane and space, vi, 63.
Types of projective transformation of the plane, viii, 43.

U.

Uintacrinus socialis Grinnell, notes on, iii, 19.
Underflow in western Kansas, iii, 121.
Unicursal curves by methods of inversion, i, 47.
quartics, Cayley's method for, i, 57.
Universal drawing curve, vii, 172.
University of Kansas, bibliography of scientific publications by members of, viii, 138.
Upper Carboniferous, the, in southern Kansas, vi, 149.
Uromyces graminicola, i, 125.
spartinæ, i, 125.
Ustilago zeæ-mays, effects of, i, 130.
hosts of, i, 132.
mycelium of, in tissues of zeæ-mays, i, 124.

V.

Vertebrate remains from the lowermost Cretaceous, iii, 1.
Visual perception of distance, v, 109.
Volucella anna, iii, 240.
apicifera, iii, 241.
avida, iii, 241.
comstocki, iii, 240.
esuriens, iii, 240.
facialis, iii, 240.
fasciata, i, 41; iii, 241.
haagii, iii, 241.
isabellina, iii, 241.
obesa, iii, 241.
satur, iii, 241.
tau, iii, 241.
victoria, iii, 247.

W.

Waconda spring, i, 85.
War expenditures, v, 76.
War spirit, causes of a rising, v, 71.
Water, Louisville mineral, vi, 117.
Waters of the Kaw river and its tributaries, chemical examination of, iii, 91.
Well irrigation in western Kansas, iii, 126.
Welsh settlements in Kansas, iii, 161.
Wheat, number of parasites of, i, 123.
Wheat starch as an adulterant of buckwheat flour, vii, 38.
Wheatstone's bridge, alternating currents in, vii, 31.
White arsenic, microscopic comparison of samples of, ix, 255.
Williamson, reference to calculus of, i, 89, 90.
Windmills, power of twelve-foot, vi, 191.
results of tests of, vi, 89.
theoretical and measured pumping power of, iv, 93.
for raising water, iii, 127.
Wind velocity at Dodge City, iii, 118.
Word-list, dialect, i, 95, 137.
Wycoff limestone, named, ii, 111.

X.

Xanthogramma habilis, iii, 238.
Xerobates? undata, skull of, vii, 143.

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Xiphactinus Leidy, a preliminary description of the opercular and other cranial bones of, viii, 19.
individual variations in the genus, vii, 115.
Xiphactinus audax, vii, 119.
brachygnathus, n. sp., viii, 107.
molossus, vii, 115.
thaumas, vii, 115.
Xylota analis, iii, 241.
coloradensis, iii, 247.
ejuncida, iii, 245.
flavitibia, iii, 244; i, 38.
Xylota metallifera, iii, 247.
notha, iii, 247.
pigra, iii, 247.

Y.

Yellow helium line, note on, viii, 85.
Yoldia glabra, n. sp., viii, 133.

Z.

Zenochætta, ii, 166.
dichromata, ii, 166.
Zoospores of Algæ, apparatus for the study of, vii, 112.

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